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Employing Acoustic Emission for Cost-Effective Continuous Monitoring of a Multi-Bolt Joint

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Abstract

Bolt loosening in mechanical joints remains one of the critical challenges in maintaining the structural integrity of industrial systems. In this study, a novel approach is proposed for monitoring the loosening status of bolts in a multi-bolt joint using low-sampling-rate acoustic emission (AE) signals. An experimental setup consisting of a four-bolt connection was designed, and acoustic signals were recorded under sixteen different bolt-tightening configurations. To analyze the signals, Mel-frequency cepstral coefficients (MFCCs) were extracted as feature vectors, and the root mean square deviation (RMSD) index was employed to quantify signal variations. The results showed that bolt loosening led to a noticeable increase in RMSD compared to the healthy state. However, no significant correlation was observed between the number of loosened bolts and RMSD values. Subsequently, five classification scenarios were designed, and the performance of a feedforward neural network was evaluated. The highest classification accuracy of 94.44% was achieved in the scenario where connections with one loosened bolts or more were separated from the rest. The proposed method, while relying on simple hardware and lightweight data, demonstrated high accuracy in the early detection of bolt loosening and shows strong potential for integration into continuous structural health monitoring systems in industrial environments.

Keywords: Bolt loosening; Acoustic emission; Low sampling rate; Mel-frequency cepstral coefficients.

1. Introduction

In the design and operation of industrial and engineering structures, mechanical joints play a crucial role in ensuring safety and performance stability [1]. Among them, bolts have become one of the most common joining methods due to their structural simplicity, ease of installation and removal, and relatively low cost. However, one of the major challenges associated with such connections is the gradual loosening phenomenon under dynamic and vibrational loads, which may lead to a reduction in preload, an increased risk of fatigue failure, and even total collapse of the system [2]. Therefore, the development of methods for continuous and accurate monitoring of bolt preload, particularly under real operating conditions, is considered an essential requirement in various industries.

Among all available techniques, the use of acoustic emission (AE) signals as a tool for monitoring bolt conditions has attracted particular attention in the scientific community. The main advantages of this approach include low equipment cost, ease of application using lightweight hardware, and the capability to be employed for long-term and continuous monitoring [3]. In this method, similar to certain other techniques, the transmitter and receiver points are positioned on opposite sides of the joint, and the transmitted signals are analyzed.

Although significant progress has been achieved in detecting loosening in single-bolt joints, monitoring the condition of multi-bolt connections still remains a complex issue and a subject of ongoing research [4]. In this study, a novel approach for detecting loosening in a multi-bolt joint is proposed. At the first stage, a single-bolt joint is examined independently, and the key features influencing loosening detection are extracted. Then, by extending these features to a four-bolt joint, the effects of different loosening scenarios (individual or combined) are analyzed

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2. Experimental Setup

To construct a database, an experimental setup was designed and fabricated. In this setup, two steel plates with dimensions of 30 × 10 cm, a thickness of 3 mm, and a mass of 0.710 kg were joined together using four M8 bolts. The plate edges were cleaned prior to assembly to ensure proper contact.For capturing the emitted acoustic signals, a condenser microphone with a maximum frequency response of 20 kHz and a mass of 0.8 g [5] was employed, together with a sound card operating at a sampling rate of 44,100 samples per second.

The developed database consists of signals recorded from multiple independent experiments. These experiments included both healthy joints (all bolts tightened) and joints with loosened bolts in different permutations. In all experiments, the sensor location was fixed at a distance of 48 cm from the impact point. This distance was selected experimentally to reduce the effects of saturation and environmental noise in the recorded data, while avoiding excessive attenuation of the transmitted waves. The proper choice of this distance improved the signal-to-noise ratio and enhanced the repeatability of the tests. A schematic of the experimental setup and the sensor position is shown in Figure 1.

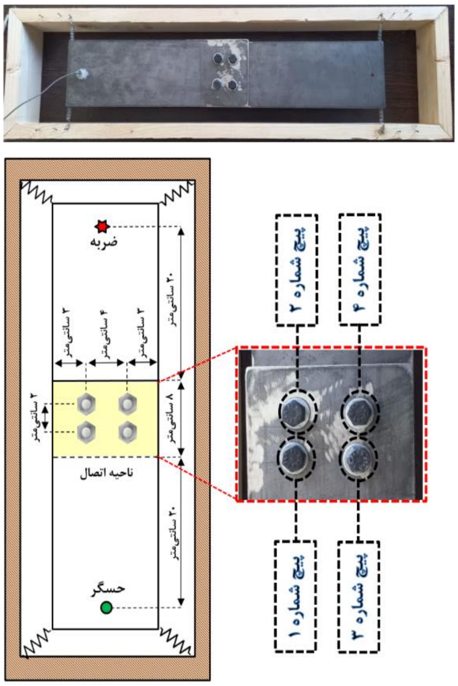

Figure 1. Test specimen and bolt positions

3. Experimental Procedure and Data

In the proposed method, the Lamb waves generated by an applied impact propagate through the joint and are recorded by the acoustic sensor. The distance between the sensor and the impact location was fixed at 48 cm. As the wave passes through the joint, it is influenced by the condition of the four bolts, so the recorded signal contains valuable information about their states.

In this study, only two conditions for each bolt were considered: fully tightened and loosened. Different permutations of the bolt states in the four-bolt joint (Figure 1) were examined according to Table 1, resulting in sixteen experimental cases.

Table 1. Bolt conditions in the joint.

Test No.	Bolt 1	Bolt 2	Bolt 3	Bolt 4
1	Tight	Tight	Tight	Tight
2	Tight	Tight	Tight	Loose
3	Tight	Tight	Loose	Tight
4	Tight	Tight	Loose	Loose
5	Tight	Loose	Tight	Tight
6	Tight	Loose	Tight	Loose
7	Tight	Loose	Loose	Tight
8	Tight	Loose	Loose	Loose
9	Loose	Tight	Tight	Tight
10	Loose	Tight	Tight	Loose
11	Loose	Tight	Loose	Tight
12	Loose	Tight	Loose	Loose
13	Loose	Loose	Tight	Tight
14	Loose	Loose	Tight	Loose
15	Loose	Loose	Loose	Tight
16	Loose	Loose	Loose	Loose

To examine the effect of the number of loosened bolts, the root mean square deviation (RMSD) values were calculated and compared across five groups, as shown in Figure 2:

- **Group I**: All bolts tight (Test 1).
- **Group II:** Three bolts tight (Tests 2, 3, 5, 9).
- **Group III:** Two bolts tight (Tests 4, 6, 7, 10, 11, 13).
- **Group IV:** One bolt tight (Tests 8, 12, 14, 15).
- **Group V**: All bolts loose (Test 16).

According to the reported data in Figure 2, the presence of a loosened bolt leads to a significant increase in the RMSD compared to the healthy joint (Group I). However, no clear correlation was observed between the number and location of the loosened bolts and the RMSD values. This phenomenon can be justified by the nonlinear and localized changes in stiffness at the joint.

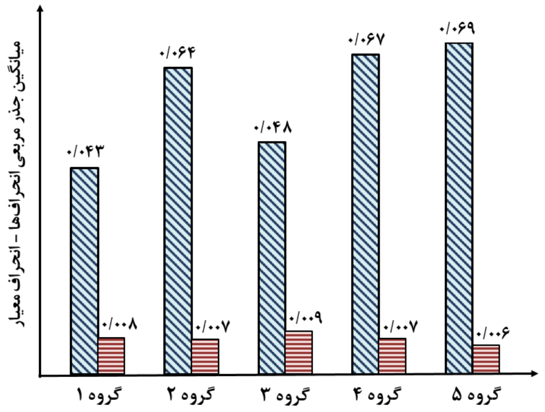

Figure 2. Average root mean square deviation of the five groups

As expected, and consistent with previous studies, the stored signals did not show major differences in the time domain. This can be attributed to the relatively low sampling rate and the geometric dimensions of the joint. Therefore, to analyze bolt loosening more accurately, the signals were transformed into the frequency domain and the average spectra of each group were calculated. The dominant frequency components were found mainly in the range of 1500–7500 Hz. Hence, the RMSD values were recalculated within this frequency band, showing that filtering the signals in this range did not significantly alter the RMSD results.

Figure 3 compares Group I (all bolts tight) and Group IV (only one bolt tight). The difference in the frequency spectra increased, and the amplitude of some peaks decreased considerably relative to the reference case. These variations were more prominent in the 2000–6000 Hz range. Figure 4 shows the comparison between Group I and Group V (all bolts loose). As expected, the differences were most significant in this case, with the main spectral peaks undergoing noticeable shifts and distortions.

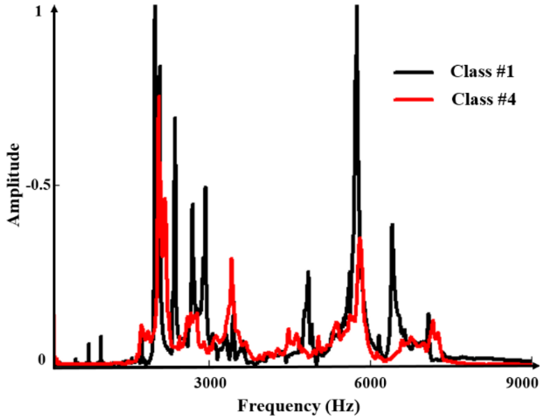

Figure 3. Comparison of the frequency spectra of the average signals recorded in Group I and Group IV tests

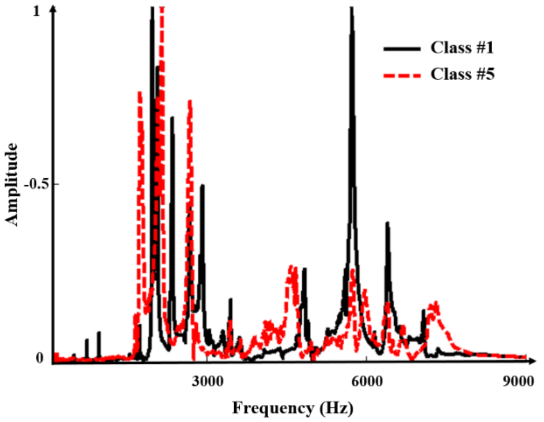

Figure 4. Comparison of the frequency spectra of the average signals recorded in Group I and Group V tests

Based on these comparisons, it was observed that the spectral differences caused by bolt loosening were more pronounced in certain frequency bands, particularly 2500–3500 Hz and around 6000 Hz. These frequency regions demonstrated higher sensitivity to stiffness changes in the joint and provided clearer distinctions between healthy and defective states.

4. Results and Discussion

According to the results reported in the previous section, the recorded signals demonstrated higher sensitivity to bolt conditions in the frequency domain compared to the time domain. Therefore, to extract appropriate features for determining the bolt conditions in the joint, each recorded signal was represented by a feature vector. This feature vector included coefficients extracted for each experiment.

The dataset consisted of 30 repetitions across 16 different experiments, totaling 480 signals. Each of these 480 signals was represented by a feature vector of length 50. To perform a more detailed analysis, five scenarios were designed in which experiments with similar physical and dynamic behavior were grouped together:

- **Scenario 1**: Each experiment was considered as an independent group, resulting in 16 separate groups.
- **Scenario 2**: Experiments were divided into five distinct groups as follows:
  Group I: All bolts tight (Test 1).
  Group II: Three bolts tight (Tests 2, 3, 5, and 9).
  Group III: Two bolts tight (Tests 4, 6, 7, 10, 11, and 13).
  Group IV: One bolt tight (Tests 8, 12, 14, and 15).
  Group V: All bolts loose (Test 16).
- **Scenario 3**: Experiments were divided into two groups:
  Group I: Three or more bolts tight (Tests 1, 2, 3, 5, and 9).
  Group II: Two or more bolts loose (Tests 4, 6, 7, 8, 10, 11, 12, 13, 14, 15, and 16).
- **Scenario 4**: Experiments were divided into two groups as follows:
  Group I: Two or more bolts tight (Tests 1, 2, 3, 4, 5, 6, 7, 9, 10, 11, and 13).
  Group II: Three or more bolts loose (Tests 8, 12, 14, 15, and 16).
- **Scenario 5**: Experiments were divided into two groups:
  Group I: All bolts tight (Test 1).
  Group II: At least one bolt loose (Tests 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16).

For the classification of the generated dataset, a feedforward artificial neural network (ANN) [6] was employed. The designed ANN included two hidden layers with 150 and 100 neurons in the first and second layers, respectively. The network parameters were selected based on experimental trials and validation performance to ensure sufficient capacity for separating nonlinear patterns while maintaining manageable complexity for the dataset.

To prevent overfitting, the dataset was divided into training (70%), validation (15%), and testing (15%) subsets. The maximum number of training epochs, minimum gradient, and initial learning rate were set to 500, 1×10^{-7}, and 0.01, respectively

Table 2. Results of trained networks for different scenarios

Scenario	Number of groups	Accuracy (%)
1	16	47.22
2	5	70.83
3	2	83.30
4	2	90.97
5	2	94.44

Overall, the results indicate that the definition of groups and the structure of the grouping have a significant effect on the classification model's performance. Increasing the number of classes and the similarity between groups decreases classification accuracy, whereas grouping experiments with clear physical and dynamic differences improves the model's discriminative power. Based on these findings, Scenarios 4 and 5 were identified as the most suitable classification strategies for the problem under study. These results provide valuable guidance for designing acoustic-based condition monitoring systems for mechanical structures

5. Conclusion

This study introduced a novel approach for the continuous monitoring of a four-bolt joint using acoustic emission signals. The experimental results confirmed that bolt loosening leads to measurable changes in the transmitted Lamb waves, particularly in specific frequency ranges such as 2500–3500 Hz and around 6000 Hz.

By analyzing the recorded signals in both the time and frequency domains, it was shown that the time-domain features alone are not sufficient for reliable detection. Therefore, a combination of statistical and spectral features was extracted to provide a more comprehensive representation of the joint condition.

The classification of the bolt states was carried out using an artificial neural network (ANN). The proposed framework successfully distinguished between different loosening scenarios with an overall accuracy above 90%. Although the network performance decreased slightly for intermediate cases involving symmetric loosening patterns, the method demonstrated robust performance for practical monitoring applications. The main advantages of the developed method are its low cost, simplicity of the hardware setup, and its ability to operate in long-term and continuous monitoring scenarios. These characteristics make it suitable for industrial applications where safety and reliability are highly dependent on the integrity of bolted joints.

In summary, the results of this research highlight the potential of acoustic emission-based monitoring as an efficient tool for detecting loosening in multi-bolt connections. Future studies can expand this approach by including more complex joint geometries, different loading conditions, and advanced machine learning algorithms to further enhance classification accuracy and practical applicability

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