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MULTI-BOLT LOOSENING MONITORING USING AN INTEGRATED VIBRO-ACOUSTIC MODULATION TECHNIQUE

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ABSTRACT

This paper proposed an integrated vibro-acoustic modulation method (IVAM) for multi-bolt loosening monitoring. Numerical simulations and experiments of a single bolt model are initially conducted to illuminate the contact acoustic nonlinearity (CAN) and vibro-acoustic modulation (VAM) phenomenon. The finite element model considers the coupled field effects and the contact interface of the bolted joint. A pumping wave with a certain low frequency combined with a probing signal sweeping through the frequency range of 50 kHz to 100 kHz was implemented and verified to effectively trigger VAM on the bolted connection. A comprehensive damage index (CDI) associated with the linear energy and nonlinear CAN change due to the bolt looseness is then proposed to evaluate bolt looseness in a full life cycle. For further study, IVAM is applied on a complex multi-bolt connection part to locate and identify the loosened bolts. Several cases are investigated to analyze its performance. An intelligent self-verification mechanism is used to ensure the accuracy of the results. The proposed IVAM method with an outcome CDI matrix possesses great application potential for multi-bolt connection monitoring with high sensitivity and accuracy. This paper finishes with summary, concluding remarks, and suggestions for future work.

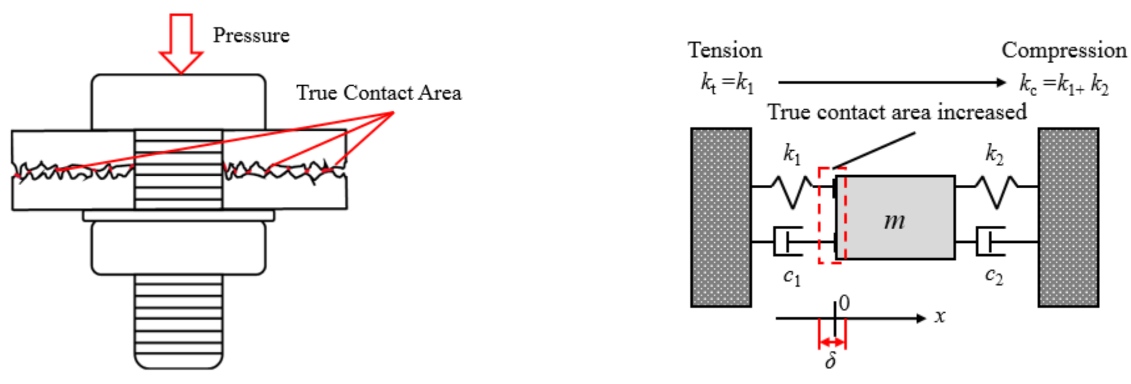
Keywords: finite element method, contact acoustic nonlinearity, vibro-acoustic modulation, multi-bolt loosening monitoring, structural health monitoring

1. INTRODUCTION

Structural health monitoring (SHM) is drawing increasing attention among engineers and researchers due to innumerous catastrophic structural failures in the past decades. Bolted joints are widely used in civil, mechanical, and aerospace industries for connecting structural elements. The bolt loosening may occur at critical locations, which would considerably threaten the integrity and safety of engineering infrastructures. Thus, it is of great importance to developing a sensing system for monitoring the bolt status. Among prevailing methods, acoustic/ultrasonic techniques enabled by piezoelectric wafer active sensors (PWAS) have recently been intensively adopted due to their advantages of high sensitivity and large inspection area coverage [1,2,3]. The principle of this method is that the decrease in the pre-tightening force caused by the loose bolt will change the characteristics of the contact surface, such as damping, stiffness and actual contact area. The sensors will detect different responses after waves passing through different contact surfaces [4]. Yang and Chang proposed a diagnostic method based on energy attenuation to identify the location of loose bolts, and estimated the bolt torque through Hertz contact theory, which provides a basis for this monitoring method [5]. Wang et al. subsequently applied two PZT patches, one as an exciter and the other as a receiver, to verify the feasibility of the theory [6]. Parvasi et al. proposed a time-domain inversion technique based on the energy method, which correlated the peak value of the received signal with the bolt axial load. They further applied numerical simulations and experiments to verify it [7]. In addition to the linear method of energy method, nonlinearity due to the different contact surfaces also is considered. Amerini et al. developed the power spectral density (PSD) of the recorded signal to evaluate the slack state of the bolt joints, and used the sound moment method, the second harmonic method and the sideband method to analyze the tightening and loosening state indicators and their relationships between applied torque [8,9].

Shen et al. used nonlinear ultrasonic spectroscopy, combined with numerical simulation and experiments, to verify that the contact acoustic nonlinearity (CAN) generated by the interaction between guided waves and the contact surface can be used as an index for evaluating bolt tightness [10]. In addition to the above impact modulation (IM) methods, the vibro-acoustic modulation (VAM) has attracted widespread attention, which does not require complex and expensive equipment to excite and analyze signals compared to other nonlinear methods. Donskoy and Sutin firstly illustrated this technique in detecting cracks in a solid plate [11]. Meanwhile, Zaitsev found the theoretical relationship between the crack size and the modulation level to the sensitivity of VAM test in crack detecting [12].

The possibility to use this method in bolt loosening monitoring was proved by Zhang et al. by a numerical and experimental study [13]. An enhanced theoretical contact model with translational spring and rotational spring was adopted to perform the bolted joints. By experiments, the feasibility and advantage of this method were verified. Besides, Wang and Song combined the revised time-reversal method with the VAM method to achieve the bolt early looseness monitoring [14]. Gnome Entropy was introduced by them to quantify the complex modulated ultrasonic waves. Inspired by their study, a novel VAM method based on the Gnome Entropy was proposed by Wang and Song in multi-bolt loosening monitoring. Even though some studies have investigated in using VAM methods for bolt loosening monitoring, there are still many limitations [15]. For example, the existing multi-bolt loosening monitoring method requires prior knowledge of loosening bolts arrangement, which is unpractical in some industrial structures. Thus, a method to find the random loosened bolts in multi-bolts connection is very attractive and valuable. In this paper, a smarter integrated vibro-acoustic modulation method (IVAM) was developed to outperform the conventional VAM with higher sensitivity. This technique can be self-verified to ensure a believable feedback.



(a) (b)

FIGURE 1: (A) MICRO INTERFACE OF BOLTED JOINT; (B) NONLINEAR OSCILLATOR MODEL FOR THE CONTACT AREA.

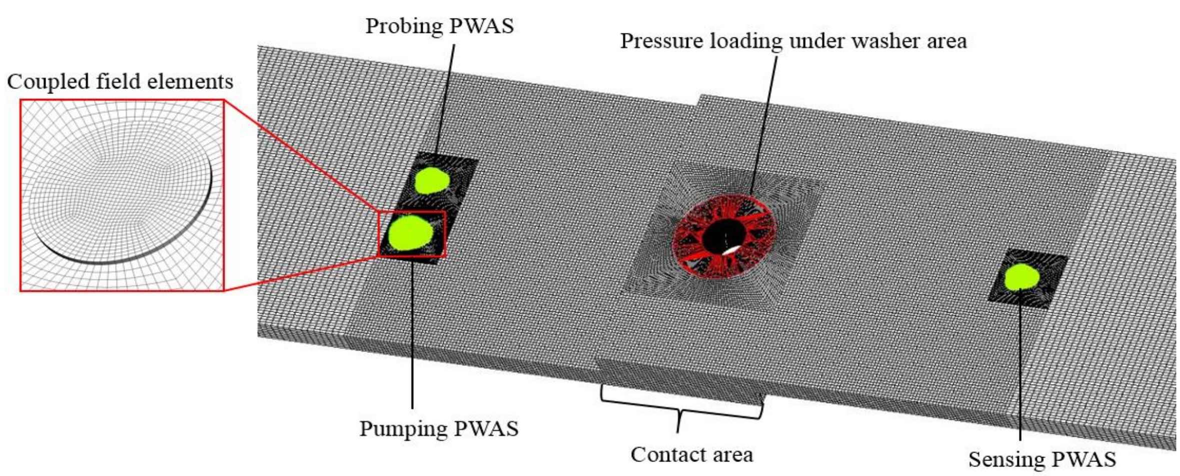


FIGURE 2: COUPLED FIELD FINITE ELEMENT MODEL.

2. THEORETICAL BACKGROUND AND METHODOLOGY

Under the microscope, the flat surfaces of solid machined components, such as the steel plates, are rough with randomly distributed severities. Therefore, the true contact area is smaller than the nominal contact area. Figure 1(a) shows a typical interface of the bolted connection. The true contact area gets increased with an increment of the preload pressure. When the ultrasonic wave is introduced, the energy dispersion will be determined by the area based on the Hertz contact theory and sinusoidal surface model. The propagated energy is proportionate to the fastening load. Consequently, the difference of energy can be adopted to detect bolt loosening. Meanwhile, the interface will be closed and opened by passing waves with a certain degree of compression and tension. Physically, the stiffness of the contact interface is changed with the relative motion. The stiffness and damping of the tensile surface will be less than the compressed surface and introduces a softening effect based on the classic nonlinearity theory, which is illustrated by figure 1(b). In a sourced sensing signals, this stiffness change is regarded as the contact acoustic nonlinearity (CAN). It brings the nonlinear stress-strain relationship in the VAM method, to generate the side-band effect in the frequency spectrum. The combination of high frequency f_H and low frequency f_L will produce the additional components at $f_H \pm n \cdot f_L$, where n is a positive integer. Accordingly, the extra part due to the CAN tells the bolt loosening. More importantly, this special characteristic would be useful to catch the looseness at very early stage, which cannot be detected by slight energy dispersion.

However, there are some challenges for the nonlinear VAM method in practice. It has been found the selection of high and low frequency would be significant to get a sensitive and credible result since some frequency combinations would be preferred to generate an observable side-band result for damaged structures. The prior knowledge should be collected with numerous tests before the monitoring, which is commonly impractical in field engineering. Besides, the VAM method only performs well in a limited range of applied torques. In experimental study, it was shown that the side-band component conversely decreased under slight remained pressure. This might misadvise a result of fully tightened status. To solve these problems, this paper utilized the certain resonance low frequency wave and swept high frequency wave to modify the traditional VAM method. When the swept frequency signal passes through the loosened bolts, several modulated parts of different high frequencies in a certain range would be acquired. This avoids checking the high frequency combination case by case, leading to a more efficient evaluation. Piezoelectric wafer active sensors (PWAS) were adopted as convenient enablers for this modified VAM method. Meanwhile, to simplify the analysis of the received signals and simultaneously realize a precisely comprehensive life cycle detection for bolted joints, a comprehensive damage index (CDI) was proposed to quantify the looseness status. The CDI is a summation of linear and nonlinear parts. The linear part can be evaluated by

$$CDI_{linear} = \frac{20\log(V_{LT})}{100 \cdot 20\log(V_{LR})} \tag{1}$$

where V_{LT} is the amplitude of the low frequency component in the transmitted pumping signal and V_{LR} is the amplitude of the pumping frequency component in the received signal.

Since the frequency changes, the frequency response is complex for identifying the amplitude of every modulated component. It might introduce errors if the amplitude of one harmonic part is adopted based on the traditional calculation method. Therefore, considering evaluating the pattern with the sum of different order harmonic amplitude. the nonlinear counterpart is calculated by

$$CDI_{nonlinear} = \frac{\sum_{i=1}^{n} 20\log(V_{SDi})}{100 \cdot 20\log(V_{HR})} \tag{2}$$

where V_{SDi} and V_{HR} denote the ith-order sideband amplitude and the amplitude of the high frequency probing wave, respectively.

Therefore, the CDI can be represented in the form of:

$$CDI = \frac{CDI_{nonlinear}}{\sqrt{CDI_{nonlinear}}} + \frac{CDI_{linear}}{\sqrt{CDI_{linear}}} \tag{3}$$

Note the minimal value of the CDI might not be 0 since Eq. (1) and Eq. (2) are proportional formulas.

The procedure to apply this integrated VAM (IVAM) method can be practiced in the following steps:

STEP 1: Apply tripped sine wave on the specimen to find a relatively low natural frequency for the VAM method.

STEP 2: Excite a swept sine wave of high frequency as the probing signal and a sine wave with the measured low frequency as the pumping signal.

STEP 3: Record and process the received signal with a high-pass filter in computer, calculating the CDI with normalized linear and nonlinear components in Eq. (1) ~ (3).

3. NUMERICAL AND EXPERIMENTAL STUDIES FOR SINGLE BOLT MODEL

To develop an in-depth understanding of this methodology, it is essential to conduct the simulation and experiment on a single bolt showcase. In this section, a three-dimensional multi-fields transient dynamic contact finite element model (FEM) was established in commercial finite analysis software ANSYS. Meanwhile, a single bolt monitoring experiment was conducted to compare and verify the simulation result.

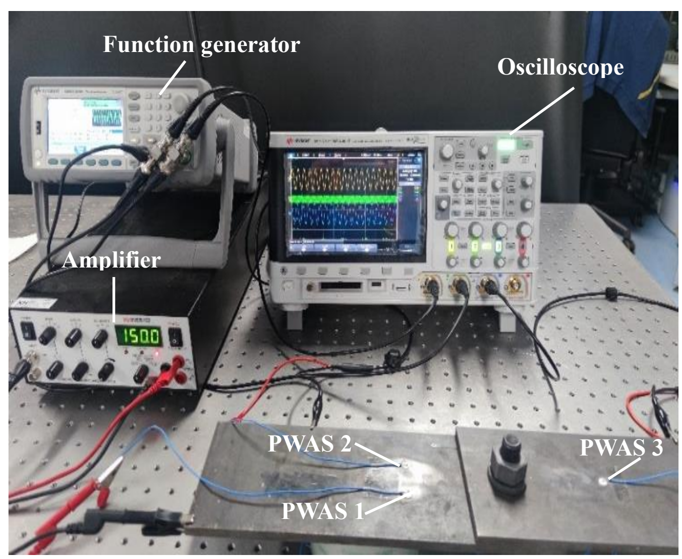


FIGURE 3: EXPERIMENTAL SETUP FOR THE SINGLE BOLT SHOWCASE.

3.1 Numerical model of the single bolt connection

Figure 2 shows the FEM for investigating the integrated VAM method with a bolted lap joint. The structure is made of two 300mm × 100mm × 8mm Q345D steel plates, which are widely used in engineering. The diameter of the washer is 16mm. The transmitter PWAS transducers including the pumping and probing parts are placed symmetrically to the bolt. The receiver PWAS also is symmetrically placed to the bolted connection.

The coupled field finite elements SOLID5 were used to couple electrical and mechanical properties in piezoelectric materials. The contact area was simulated by a contact pair, CONTA174 and TARGE170. The element size of the important part for calculation was selected as 1mm × 1mm × 1mm. The preload of the bolted joint was from the loaded pressure on the washer area. The following formula presents how to calculate the pressure:

$$P = \frac{T}{kdA} \tag{4}$$

where P is the pressure, T is the applied torque, k represents the torque coefficient which depends on a variety of parameters including but not limited to geometry and friction of the threads, d is the nominal diameter of the bolt, and A is the washer area.

Three representative cases with 25N·m, 35N·m, and 40N·m were introduced to simulate the loosened status and the tightened status, respectively. The pumping wave and probing wave generated by the transmitter PWAS pass through the bolted connection and interact with the contact surface to achieve VAM, being detected by the receiver PWAS. The analysis result of the sensing signals will be compared with experimental study.

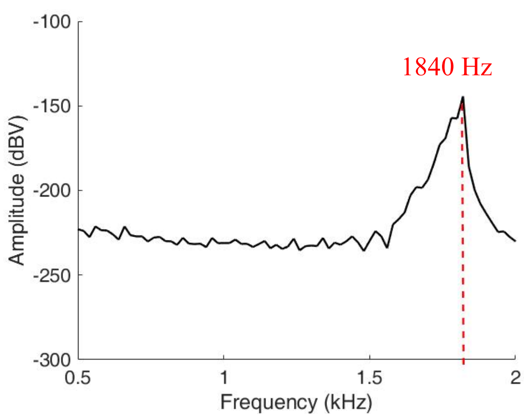


FIGURE 4: RESONANCE RESPONSE TO 500-2000Hz CHIRP EXCITATION.

3.2 Experimental setup for the single bolt connection

The experiment setup for the integrated VAM method is illustrated in figure 3. The single-bolt specimen was made of two 300 mm × 100 mm × 8 mm rectangular Q345D steel plates fastened by an M16 bolt, similarly to the simulation design. Three PWAS transducers were bonded on the specimen of the same size in simulation. PWAS 1 and 2 are the pumping and probing actuators, respectively, and PWAS 3 is the receiver. A Keysight 33500B function generator was adopted to apply the pumping and probing excitation signals. The pumping signal was then amplified by a Krohn-hite 7602M power amplifier to throw to the PWAS 1. The two kinds of guided waves propagated along the plate from the transmitter to the receiver and interacted with the lap joint to generate the VAM, and finally were picked by the receiver PWAS 3. The sensing signals were recorded by the Keysight DSO-X 3014T digital oscilloscope.

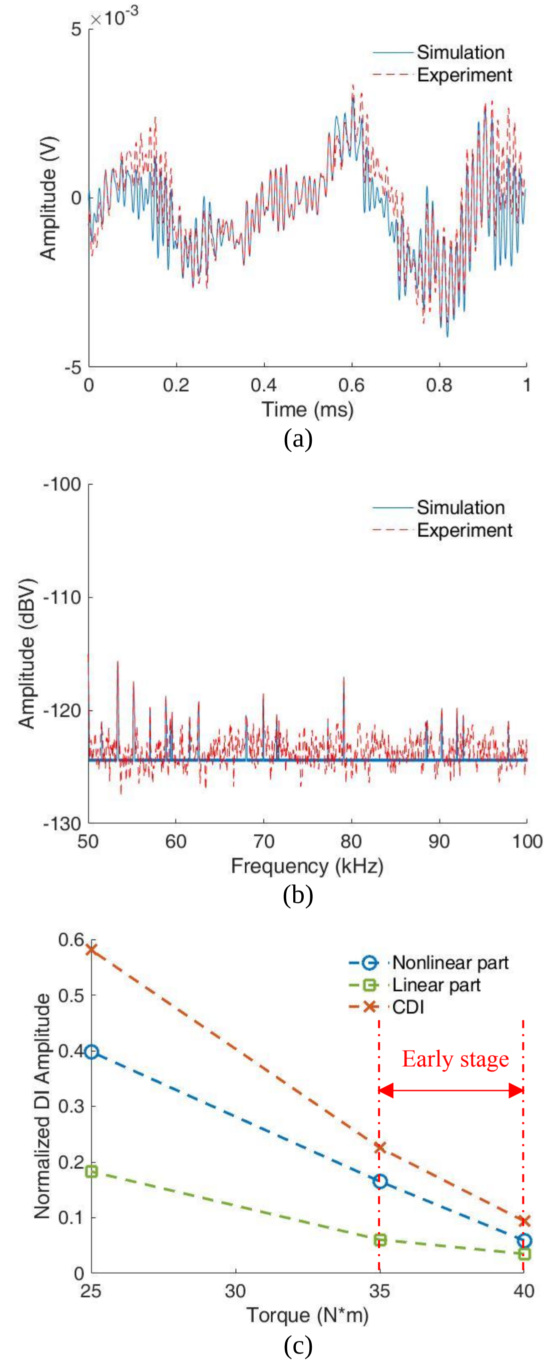
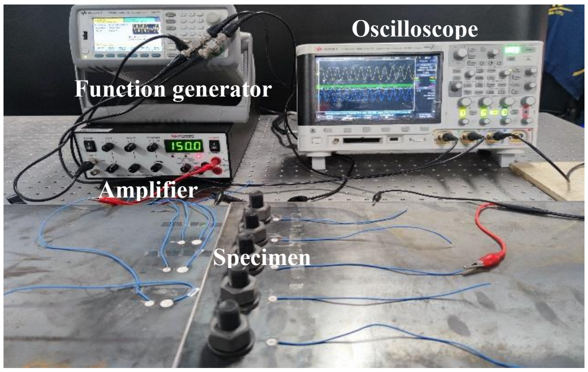
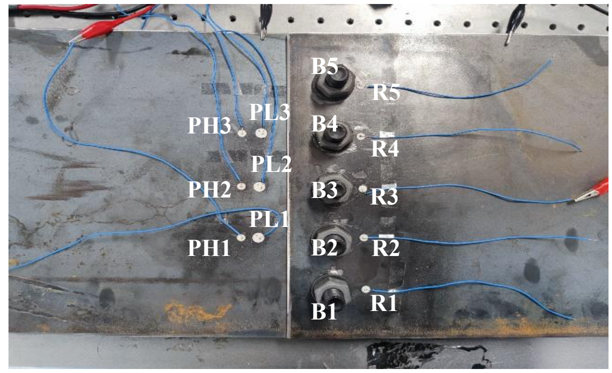


FIGURE 5: EXPERIMENTAL RESULTS WITH 25 N·M: (A) TIME DOMAIN RESULT; (B) FREQUENCY DOMAIN RESULT; (C) CDI RESULT.

A chirp signal with the amplitude of 10Vpp and frequency range of 500 Hz-3 kHz was firstly applied on PWAS 1 to find the natural frequency of the structure. A series of low-order natural frequencies of the structure was obtained, as shown in figure 4. To realize a maximum extent of CAN, the frequency of 1840 Hz was selected as the pumping frequency f_L to form a 150Vpp continuous sine wave. Then, a swept sine wave with the amplitude of 10Vpp and frequency range of 50 kHz-100 kHz would be triggered as the probing wave synchronously to implement the IVAM method. The same actuated signals were excited in the simulated model for comparison. Based on our computational source, the period of this chirp signal was set to 1ms.



(a)



(b)

FIGURE 6: EXPERIMENTAL SETUP FOR MULTI-BOLT CONNECTION: (A) THE OVERVIEW; (B) THE ARRANGEMENT OF THE PWAS ARRAY.

3.3 Data analysis and result discussion for the single bolt showcase

A typical sensing signal in experiment was presented in figure 5, when the remained torque is 25 N·m. The results demonstrated a considerable similarity between the experiment and simulation. The distinctive nonlinear harmonic response appeared in the spectrum of experiment and simulation, which is corresponding to our theoretical analysis. This indicates the nonlinearity of the lapped joint can be properly simulated by our contact model. It should be noticed that the experimental study produced many complicated patterns in the time and frequency domain. However, the majority of such unfavorable parts would be ignored after filtering and demodulation, considering the only interest of our CDI calculation is the harmonic characteristic. Figure 5(c) presents the CDI results from three representative cases. The linear part was found to be insensitive to the early-stage loosening, which is corresponding to previous studies. The implementation of nonlinearity persuasively improves the CDI performance in detecting slight looseness in bolted connections. It was found that the minimum value of the CDI is not zero, as stated in section 2. Thus, we can assume the bolts are fully tightened with a CDI less than 0.1.

4. MULTI-BOLT EXPERIMENTAL SETUP

In this section, the proposed IVAM technique was utilized to monitor the multi-bolt connection of two steel plates. As illustrated in figure 6, the specimen contains two 600 mm × 200 mm × 5 mm Q345D steel plates held through five M16 bolts, which are denoted as B1 to B5. To detect the bolts with accuracy and efficiency, a PWAS array is prudently designed and bonded on the specimen. The intelligence of this array is to enable an approximately equivalent distance between every pair of transmitter and receiver PWAS with the minimum number of pumping sources. Thus, self-verification can be achieved by comparing the received signals from other transmitters. For example, the center bolt B3 and its corresponding receiver can detect the signal from two different transmitters of the same distance. Meanwhile, the defective bolts can be located precisely by cross information exchange between different pairs. For convenience, three d_{33} pumping patches (size: 10 mm × 0.5 mm) were named as PL1, PL2, and PL3, three d_{31} probing patches (size: 7 mm × 0.2 mm) were tabbed as PH1, PH2, and PH3, five d_{31} receivers (size: 7 mm × 0.2 mm) were denoted as R1 to R5.

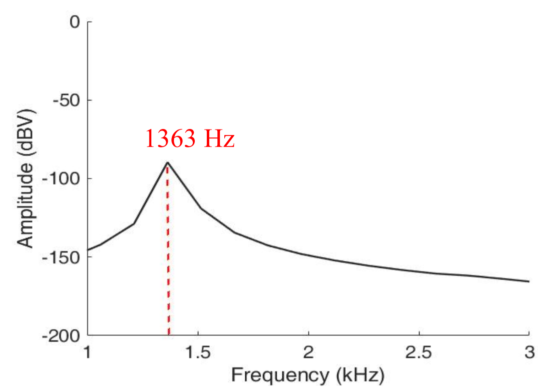


FIGURE 7: RESONANCE RESPONSE OF MULTI BOLTED CONNECTION TO 1000-3000Hz CHIRP WAVE.

The natural frequency of this connection was found at 1363 Hz, as illustrated in figure 7. Then, in practice, PL1, PL2, and PL3 would be excited by a continuous sine wave with a frequency of 1363 Hz and an amplitude of 150Vpp and PH1, PH2, and PH3 would be fed by a linear swept sine wave with a frequency range of 50 kHz-100 kHz, a period of 1ms, and an amplitude of 10Vpp synchronously. The duration of the swept signals was set as 1 second. The modulated waves were captured by corresponding sensors R1 to R5 and recorded by the oscilloscope with a sampling rate of 100 MHz after propagating the lapped joints. TABLE 1 provides different cases of bolted joints status. For each case, we conducted five times tests and adopted the average value for the conclusive CDI computation.

TABLE 1: DETAILED EXPERIMENTAL SCENARIOS.

Case	B1	B2	B3	B4	B5
1	40 N·m	40 N·m	40 N·m	40 N·m	40 N·m
2	30 N·m	30 N·m	30 N·m	30 N·m	30 N·m
3	20 N·m	20 N·m	20 N·m	20 N·m	20 N·m
4	10 N·m	10 N·m	10 N·m	10 N·m	10 N·m
5	0 N·m	0 N·m	0 N·m	0 N·m	0 N·m

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5. MULTI-BOLT TEST RESULTS

By implementing the procedure described in section 2, the time-trace modulated waves and corresponding frequency spectrum of every case was obtained. Figure 8 presented representative modulated waveforms captured by R3 with 25 N·m. It should be noticed higher energy was reserved through the multi-bolt connection than the single bolted joint with the same torque and excitation. Meanwhile, added bolts brought more extra components in the detected frequency spectrum. Unpredicted interactive behaviors happened with multi-bolt joints to bond them together and induce the complexity of the analysis.

Thus, to enable monitoring with accuracy, our system built a self-verification mechanism. It has been identified that the PL1 and PL3 are symmetrically placed about the R3. Thus, self-verification can be conducted by comparing received signals from PL1 and PL3. In this case, it reveals significant comparability. The high amplitude response similarly happened on some certain frequency parts. Therefore, this result is acceptable for our later analysis.

The CDI of each different case was computed and displayed in figure 9. Data was processed from five times average experiments. A clear increasing trend for CDI is observed with the torque decreasing on each bolt. Furthermore, high sensitivity is uncovered on early-stage looseness i.e., 30 N·m to 40 N·m. Also, the CDI amplitudes of B1 and B5 are higher than others with the same load condition. This might because the multi-bolt connection kept better integrity at the center of joints. In general, the differences of CDI among different bolts are not obvious, while all these cases have a sensitive and precise performance in a whole life cycle bolt monitoring. Therefore, based on the reliable and self-verifiable PWAS array and our CDI method, the defected bolts can be effectively identified and located in multi-bolt connection by setting a "conversation" between any pair of transmitters and receivers. This IVAM evaluation is capable of tracking the full life-cycle of bolted joint structures.

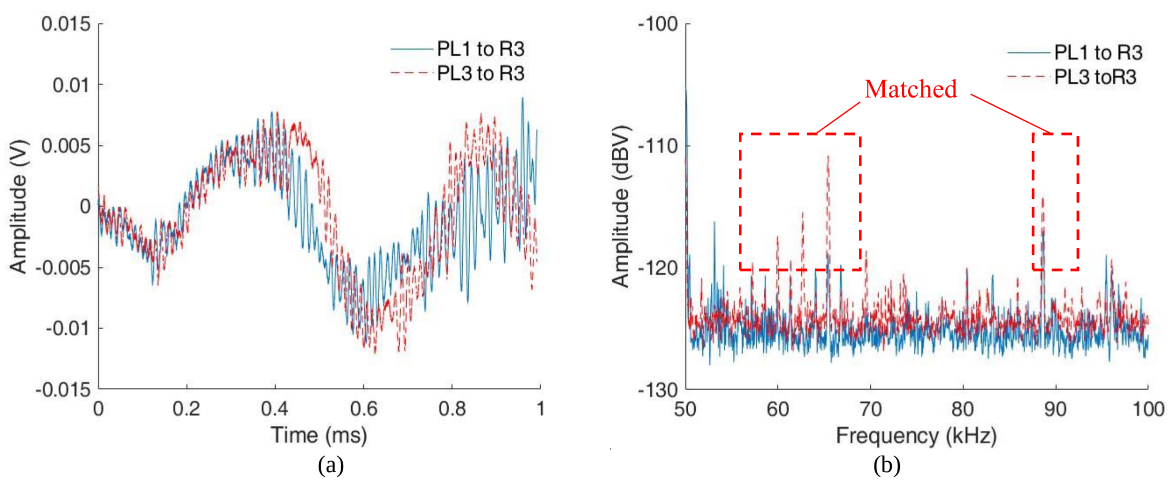

FIGURE 8: SELF-VERIFICATION RESULTS USING PWAS PL1-R3 AND PL3-R3 PAIRS (A) RECEIVED SIGNAL IN TIME DOMAIN AT PWAS R3; (B) RECEIVED SIGNAL IN FREQUENCY DOMAIN AT PWAS R3.

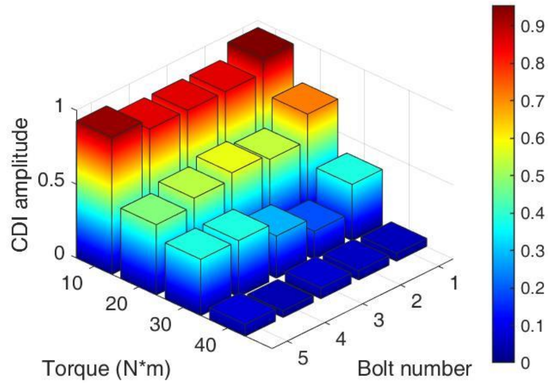

FIGURE 9: EXPERIMENTAL RESULTS FOR THE MULTI-BOLT CONNECTION WITH DIFFERENT TORQUE LEVEL.

6. CONCLUDING REMARKS AND FUTURE WORK

This paper presented a novel integrated vibro-acoustic modulation (IVAM) method with a comprehensive damage index (CDI) to realize multi-bolt loosening monitoring and to track the entire life cycle of a loosened bolt. A three-dimensional coupled-field transient FEM was investigated to deeply understand the mechanism of VAM. The single bolt model experiment was conducted for comparison. A low pumping frequency was found by the swept wave experiment and a swept sine wave within the range from 50 kHz to 100 kHz and the period of 1ms was selected to be the probing signal. With three different cases of preload applied on the bolted joint, numerical and experimental results demonstrated the effectiveness of the IVAM. Then, a multi-bolt monitoring system with a PWAS array was prudently designed to identify and locate the deficiency. This technique contains a self-verification mechanism by comparing the received signals from two symmetric transmitter pairs. The results illustrated that our IVAM method is applicable in different cases of looseness. This might bring more potential for future SHM and NDE applications.

For future work, further study of the nonlinearity information processing for bolt looseness detection will be conducted. Also, automation data acquisition and processing should be considered to make it more applicable in the advanced industry.

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