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Vibro-Acoustic Modulation (VAM)-inspired Structural Integrity Monitoring and Its Applications to Bolted Composite Joints

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Abstract

Vibro-acoustic modulation (*VAM*) – one of the prevailing nonlinear methods for material characterization and structural damage evaluation – is based on the effect of modulation of a low-frequency vibration (pumping vibration) on a high-frequency acoustic wave (probing wave). In this study, the contact acoustic nonlinearity (*CAN*), associated with changes in the solid-solid interface of a bolted joint under *VAM*, due to bolt loosening, is explored analytically and experimentally, on which basis a *VAM*-inspired approach is developed for monitoring structural integrity of bolted joints. Numerical simulation based on a theoretical model with structural nonlinear contact stiffness is implemented, to achieve insight into *CAN* induced by a loose bolt. A quantitative correlation between vibro-acoustic nonlinear distortion and degree of bolt loosening is ascertained. The developed approach is applied to detect bolt loosening in a composite bolted joint and to evaluate the residual torque of the loose bolt quantitatively. Take a step further, *VAM*-based nonlinear approach is compared against elastic wave-based linear methods, underscoring a higher sensitivity to bolt loosening. From early awareness of bolt loosening to continuous evaluation of the bolt loosening progress, this *VAM*-based approach has provided a cost-effective framework for monitoring the health and integrity of a composite bolted joint.

***Keywords*:** composite bolted joint; bolt loosening; vibro-acoustic modulation; contact acoustic nonlinearity; structural health monitoring

1. Introduction

To streamline manufacturing and enhance structural load-carry capability, there has been increased preference in assembling composite structural components through bolted joints [1, 2]. However, throughout the service life of a bolted composite joint, a wide array of diatheses including plastic deformation of threads, interfacial slip and inappropriate manipulation can initiate bolt loosening and accelerate the subsequent loosening process [3-5]. The mating parts of a composite joint undergo a large extent of creep and stress relaxation when they are subject to a dynamic load or exposed to a high temperature, due to a lack of reinforcement in the thickness direction, which can further deteriorate the loosening process [6]. The accumulation of bolt loosening downgrades the integrity of a composite joint drastically, and accordingly increases the risk of joint separation and even system failure. To put it into perspective, approximately 20% of mechanical system failures across the world are reportedly caused by bolt loosening [7]. Considering the wide applications of composite materials and structures in today's engineering assets, it is an imminent need to develop reliable, yet cost-effective techniques that are capable of identifying a loose bolt in a bolted composite joint at an early stage, and evaluating, at least qualitatively if not quantitatively, the severity of loosening.

The concept of structural health monitoring (*SHM*) has proven effectiveness in identifying bolt loosening [8]. Based on various theoretical cornerstones, a diversity of *SHM* approaches have been developed and deployed [9-11], as typified by those based on structural vibration or guided wave propagation. Vibration-based *SHM* [12], relying on the changes in structural global dynamics, can be insensitive to a loose bolt before the loosening reaches a substantial extent; while guided-wave-based *SHM* [11], exploring the changes in wave signal feature (such as delay of time-of-flight[13], wave reflection, transmission or mode conversion[14]), is often limited by the wavelength of a selected wave mode, and under most circumstances the above-stated wave features are not altered remarkably by a loose bolt. For instance, Yang and Chang [11] proposed a linear acoustic-wave-based method to identify the torque level of a loose bolt in a composite thermal protection. However, the bolt loosening when it is at a slight degree is similar to a micro-scale crack that does not induce phenomenal changes in wave features [15]. Moreover, the waves propagating in composite structures usually exhibit much complex dispersion behaviors and serious attenuation effect with a multimode of wave modes that are mutually interfered with one another [16]. Together, these traits of waves complicate extraction and interpretation of wave features, entailing sophisticated signal processing tools [17-19].

To circumvent the above deficiencies of linear acoustic-wave-based methods, recent research efforts have been focused on the development of the nonlinear acoustic-wave-based methods, in which the nonlinear features of acoustic waves are extracted, calibrated and linked to structural damage or malfunction (such as bolt loosening). Amongst various candidate approaches, those based on acoustic wave-modulation are competitive and outperforming the others in some occasions, with proven efficiency in identifying impact cracks in composite structures [20]. The essence of wave-modulation methods resides on the interaction of the interfacial contact effect (arising from fatigue cracks with a "breathing" motion pattern or from the solid-solid interface of assemblies in a bolted joint) with a mixed excitation (consisting of a pumping vibration with a frequency of f_L and a probing wave with a frequency of f_H). The interaction induces structural dynamic nonlinearity, specifically defined as contact acoustic nonlinearity (*CAN*) [21], which can be evidenced in signal spectra. Considering a bolted joint and provided all the bolts are fully fastened in the joint, the acquired signal spectrum of the mixed excitation exhibits two major power concentrations at the two frequencies at which the pumping vibration and probing wave are excited, respectively; or otherwise in the scenario with loose bolts, additional frequency components around the probing signal components are expected to be present in the spectrum – termed as left sideband (if lower than the frequency of the probing signal) or right sideband (if higher than the frequency of the probing signal). The magnitudes of the sidebands, determined by the intensity of *CAN*, can be linked quantitively to the severity of bolt loosening. Compared with other nonlinear methods, for example those by exploring the changes in second-order harmonic generation, the acoustic wave-modulation detection philosophy can, by properly selecting the frequency of a mixed excitation, minimize the influence of the nonlinearity contributed by other sources rather than the bolt loosening, such as measurement apparatus and material itself. Thus, the information on bolt loosening can be duly manifested by the acquired *CAN*, reducing the dependence on advanced signal processing [22-24].

Impact modulation (*IM*) and vibro-acoustic modulation (*VAM*) are the two major implementation modalities of acoustic wave-modulation, both of which have been demonstrated effective in characterizing various types of structural damage and fatigue cracks in particular [8, 20, 25, 26]. An *IM* method relies on the use of an impact excitation to generate signals under the natural vibration modes of an inspected structure. Representatively, Meyer and Adams [26] extended the application of *IM* to the identification of bolt loosening in an aluminum joint, and experimental data showed reasonable consistency with theoretical results. However, for an *IM* method, the signals captured under natural modes excited by an impact force are usually vulnerable to the contamination of measurement noise and uncertainties, leading to inaccurate identification results. On the other hand, a *VAM* method adopts stable vibration signals generated by a harmonic excitation with a much lower level of measurement noise involved, and therefore the nonlinear responses (*i.e.*, sidebands) can be manifested explicitly in signal spectra. Zhou *et al.* [27] investigated the detectability of a wave modulation method when used to detect bolt loosening in a metallic frame structure, and conclusion were drawn that a wave modulation-based approach was capable of accurately indicating bolt loosening even in its embryo stage. Though results are promising, the above-mentioned two studies [26, 27] are mainly focused on the detection of bolt loosening in metallic structures, and relevant research endeavor in extending such a detection principle to composite joints is still limited and worthy of investigating and validating. In addition, it is of vital necessity to underscore that most of the existing studies pertaining to bolt loosening identification based on nonlinear dynamic responses have been developed based largely on experimental observations or empirical knowledge, and rigorous theoretical investigations are far from sufficient.

In recognition of the above limitations and inspired by the proven efficiency of *VAM*-based nonlinear methods in detecting impact damage in composite structures, the present study is dedicated to quantitative characterization of bolt loosening in composite joints using the *VAM*-based nonlinear principle. To gain a theoretical insight into the essence of generation of nonlinear dynamic responses (*i.e.,* sidebands), an enhanced theoretical model of interfacial contact stiffness is established, facilitating defining the dependence of *CAN* on the contact pressure at a solid-solid interface. Integrating the developed theoretical model with a finite element (*FE*) model, numerical analysis of a bolted joint is achieved. Take a step further, a *VAM*-inspired framework is developed for monitoring structural integrity of composite bolted joints, which is experimentally validated by evaluating different degrees of leftover torques on a loose bolt in a composite-composite (*C-C*) joint. For comparison, the sensitivity to bolt loosening of the *VAM*-inspired framework is also compared with that of an elastic wave-based linear method.

2. An Enhanced Analytical Model for Interfacial Contact Stiffness of A Bolted Joint

The surface of a solid is rough with randomly distributed asperities, and consequently the solid-solid interface features partial contact when two solids come into contact. By way of illustration, **Figure 1** shows the surface morphology of a typical composite beam obtained by scanning electron microscope (*SEM*), and the cross-section *SEM* morphology of two composite beams in contact. The actual contact area of the interface increases with an augment of the contact pressure. When interacting with acoustic waves, the contact interface opens and closes if it undergoes a certain extent of tension and compression, respectively. As a consequence, the contact stiffness of the interface under compression is higher than that under tension. Physically, the application of classical nonlinearity (*i.e.,* a quadratic nonlinear stiffness) introduces a softening effect when the relative motion between the two contact surfaces of a joint is positive (*i.e.,* to open the interface) whereas a stiffening effect when the relative displacement is negative (*i.e.,* to close the interface) [19, 21]. Earlier studies [11, 24] have confirmed that linear interfacial contact stiffness is proportional to the actual contact area at the interface, which is synergistically determined by the contact pressure and surface roughness. Along the same line of thinking, when two composite structural components (denoted by *C-C* in what follows) are assembled via a bolt as displayed in **Figure 2**, a partial contact occurs at the interface [28], even when the bolt is fully fastened.

Provided that the bolt is loose to a certain extent, the accordingly reduced contact pressure at the interface induces "breathing" effect (*i.e., CAN*) when the joint is subject to a harmonic vibration. The local nonlinear contact stiffness in the mating parts (*i.e., CAN*) of the loose joint, which is associated with the residual torque remained on the bolt, dominates both the structural nonlinear stiffness and resultant nonlinear response of the joint. To facilitate comprehending of the mechanism of nonlinear distortion generation in the modulated waves (manifested as sideband magnitudes in signal spectra) when the joint is subject to a mixed excitation, it is of vital importance to ascertain the reliance of interfacial contact stiffness on the residual torque on the loose bolt. To this end, a power-law relation between the linear contact stiffness, K_L, and interfacial pressure, P, at the solid-to-solid interface is recalled, which reads

$$K_L = \begin{Bmatrix} k_L^t \\ k_L^r \end{Bmatrix} = \begin{Bmatrix} \lambda_0^t \\ \lambda_0^r \end{Bmatrix} P^m, \tag{1}$$

where k_L^t and k_L^r are the linear transitional and rotational stiffness, respectively; λ_0^t, λ_0^r and m are constants relating to asperity-height distributions along the contact surfaces.

However, in experiment, the utilization of **Equation (1)** is fairly restricted because it is a challenging task to measure the interfacial pressure. Considering that P is approximately proportional to the interfacial preload, F, and a linear relationship between F and the applied bolt torque, T, exists (according to $F = T / \tau d$, where d and τ are the bolt diameter and friction coefficient between the nut and bolt, respectively), K_L in **Equation (1)** can thus be linked directly to T, in terms of

$$K_L = \begin{Bmatrix} \lambda_1^t \\ \lambda_1^r \end{Bmatrix} T^m, \tag{2}$$

where λ_1^t and λ_1^r are the modified surface-roughness-related constants proportional to λ_0^t and λ_0^r in **Equation (1)**, respectively. The inclusion of T in **Equation (2)** makes it possible to quantitatively indicate the bolt loosening, as T is a parameter that can be acquired via measurement. Under most circumstances, most asperities on the contact surfaces in the mating parts of a joint have comparable and similar heights and curvatures, and this leads to a correlation between the actual contact area (A) and contact pressure as $A \propto P^{0.5}$ [11, 29]. Given that $K_L \propto A$ and $P \propto T$, m in **Equation (2)** is estimated to be 0.5.

As mentioned earlier, a typical interfacial "breathing" effect is induced into a loose joint when the joint is subject to *VAM*, where a rapid and periodical variation in the contact area occurs. Such a phenomenon can result in the generation of *CAN*, which, however, cannot be reflected K_L only, because K_L is the linear contact stiffness and independent of *CAN*. To circumvent this deficiency, a nonlinear contact stiffness, K_N, is introduced to model the bolted joint, which reads

$$K_N = \begin{Bmatrix} k_N^t \\ k_N^r \end{Bmatrix}, \tag{3}$$

where k_N^t and k_N^r are the nonlinear transitional and rotational stiffnesses, respectively. For simplicity, k_N^t and k_N^r are often set to be constants in previous studies [26]. However, a constant K_N obviously implies that the bolt loosening-induced *CAN* is a constant, regardless of the residual torques on the bolt and the degree of bolt loosening, and this can restrict the detection of bolt loosening in a quantitative manner. In this model, K_N is re-defined to include both the linear and nonlinear contact stiffness, as

$$K_{enhanced} = \begin{Bmatrix} K_L \\ K_N \end{Bmatrix} = \begin{Bmatrix} \lambda_1^t T^m \\ \lambda_1^r T^m \\ \lambda_2^t T^n \\ \lambda_2^r T^n \end{Bmatrix}, \tag{4}$$

where $K_{enhanced}$ is the re-defined contact stiffness. λ_2^t, λ_2^r and n are three constants related to the surface roughness and actual contact area. In particular, the case in which $n = 0$ in **Equation (4)** actually corresponds to a constant K_N as assumed elsewhere [26]. In the enhanced model, the terms in K_N are assumed to vary inversely with the actual contact area, as demonstrated elsewhere [29, 30], by setting $n = -0.5$ in **Equation (4)**. The enhanced model implies that when bolt loosening initiates and progresses, K_N increases in magnitude and augments the extent of *CAN*; and in the meantime, K_L decreases due to the reduction in the interfacial pressure and actual contact area. Therefore, $K_{enhanced}$ is linked, quantitatively, to the residual torque remained on the loose bolt.

It is noteworthy that the above discussion and modeling is independent of the types of joining material and it is therefore applicable to describe the interfacial contact behaviors of a bolted composite joint. This is to be proven using numerical simulation in the sequent session using a single-lap composite-composite (*C*-*C*) bolted connection.

3. Numerical Analysis of A Bolted Joint Using the Enhanced Theoretical Model

Based on the analytical model of interfacial contact stiffness of a bolted joint with a loose bolt, as described by **Equation (4)**, the analysis of a bolted joint is achieved, in conjunction with the use of a finite element (*FE*) method. The *FE* model developed for the joint in **Figure 2**, when the joint is subject to a mixed excitation, is shown in **Figure 3**. The model consists of two Euler-Bernoulli beam components, each containing six elements of the same length (denoted by E1~ E6) and seven nodes (N1~N7). Each node has two degrees of freedom (*DOF*s), *i.e.*, transverse deflection, w, and rotation, θ. The right end of the joint is fixed to form a cantilever beam. A spring model is used to simulate the boundary condition in the clamped end and the contact condition at the lapped portion of the joint. The spring model comprises both translational and rotational springs that joints two beams via nodes N7 and N8, to introduce contact effect between element E6 and E7. Extra masses are added to E6 and E7 to simulate the bolt and nut (see shadowed areas in **Figure 3**). In the mixed excitation, the pumping vibration and probing wave are applied to the joint at nodes N2 and N6, respectively. The dynamic responses of the joint are obtained at node N9.

The equation of motion of the bolted joint under discussion is governed by

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K_L]\{u\}+\mathbf{f}_\mathbf{c}=\{F_e\}, \quad \textbf{(5a)}$$

where $\{u\}$, $\{\dot{u}\}$ and $\{\ddot{u}\}$ are the displacement, velocity and acceleration vectors, respectively; $[M]$, [C] and $[K_L]$ are the global inertia, damping, and linear stiffness matrices in a dimension of 28×28, respectively, where $[M]$ and $[K_L]$ are assembled using local matrices established on elements, and $[C]$ can be ascertained according to Rayleigh damping assumption[31], as

$$[C]=\alpha[M]+\eta[K_L], \quad \textbf{(5b)}$$

where α and η are the two constants to be estimated by modal analysis of the joint along with λ_1^t and λ_1^r in **Equation (4)**. $\{F_e\}$ represents the external excitation vector, and $\mathbf{f}_\mathbf{c}$ signifies the nonlinear interfacial contact force vector equivalently treated as an excitation vector. Specifically, $\mathbf{f}_\mathbf{c}$ includes non-zero elements only at the nodes within the bolted area (*i.e.*, N7 and N8), and can be defined as

$$\mathbf{f}_\mathbf{c}=\left[0,...k_N^t(w_7-w_8)^2,k_N^r(\theta_7-\theta_8)^2,-k_N^r(\theta_7-\theta_8)^2,-k_N^t(w_7-w_8)^2,...0\right]^T, \quad \textbf{(5c)}$$

where k_N^t and k_N^r, from **Equation (3)**, are the translational and rotational nonlinear stiffness of the inserted springs at N7 and N8, respectively, and are weighted with the squares of correspondingly relative displacements.

With the estimated (linear and nonlinear) parameters, listed in **Table 1**, the linear and nonlinear responses of the joint subject to the pumping vibration (with a frequency of 758

Hz – with a selection criterion to be detailed in Section 4) and probing wave (with a frequency of 14.89 kHz, see Section 4 for selection criterion), under different degrees of residual torque remained on the bolt, are obtained using a solving procedure recapped in **Figure 4**. For the purpose of comparison, three scenarios are considered:

Scenario I: only the linear stiffness in the model is considered (**Equation (2)**);
Scenario II: the nonlinear stiffness in the model is considered, but the nonlinear terms are a constant (corresponding to $n = 0$ in **Equation (4)**); and
Scenario III: the enhanced analytical model is adopted, in which nonlinear stiffness is considered and the nonlinear terms vary subject to an exponential function ($n = -0.5$ in **Equation (4)**).

Figure 5 presents the spectrum of the joint, calculated using Scenario I, under the maximum degree of bolt loosening (*T*=1 N·m). Obviously, the absence of sidebands in the spectrum indicates the failure of Scenario I in faithfully depicting the dynamic response of the joint under a mixed excitation. **Figures 6** compares the spectra of the joint, at three representative levels of bolt torques (*T*= 13, 7 and 1 N·m), using Scenarios II and III. The joint under a torque of 13 N·m is considered as under a fully tightened condition according to the yielding strength of the composite specimen and the allowable tensile load of the bolt, whereas the joint under 1 N·m corresponds to a fully loosened condition. Under the bolt torque of 1 N·m, Scenarios II and III give rise to similar spectra, as shown in **Figures 6(e)** and **(f)**. The results using Scenario II include much higher sideband magnitudes compared with those calculated using Scenario III when the bolt torque increases. Obvious sidebands can even be captured in the frequency spectrum calculated by Scenario II for the joint under the fully tightened condition (*i.e.,* under 13 N·m). This has revealed that Scenarios II induces excessive sidebands due to the adoption of a pressure-independent nonlinear contact stiffness – a case inconsistent with the reality.

Allowing for the fact that the magnitudes of sidebands are synergistically dependent on both the excitation intensity of the probing wave and the degree of *CAN* [25, 30], the magnitudes of actual left (A_L) and right (A_R) sidebands are normalized with the response magnitude of probing wave at f_H (A_H) to obtain magnitudes of relative left (S_L) and right (S_R) sidebands [32, 33], in order to achieve a quantitative comparison without involvement of influence of probing wave, as

$$S_L = A_L - A_H \quad \text{and} \quad S_R = A_R - A_H . \qquad \textbf{(6)}$$

Further observation regarding variation in relative sideband magnitudes within the entire bolt torque range (from 13 to 1 N·m) underscores that a more remarkable variation in the sideband magnitudes can be observed by using Scenario III, as observed in **Figure 7(b)**, whereas Scenario II leads to much lower degree of variation in the sideband magnitudes, **Figure 7 (a)**. Such discrepancy can be attributed to the ignorance of the nonlinear property of the joint in Scenario II. Further comparison between Scenarios II and Scenario III is to be experimentally implemented in sequent section.

To conclude, with the enhanced contact model by involving nonlinear contact stiffness, numerical analysis of a bolted joint under *VAM* is achieved in this section. Regardless of difference between Scenarios II and III, the numerical results reveal that a decrease in the leftover torque of a joint leads to an increase in the sideband magnitudes in signal spectra. Based on such a quantitative correlation, an experimental framework inspired by *VAM* is developed for detecting bolt loosening and subsequently evaluating the residual torque of a loose joint.

4. Application to Composite Joints

The bolted composite joint under inspection was assembled with two beam-type components made of unidirectional T700/7901 prepreg consist of carbon fiber and epoxy matrix, using an M6 bolt, an M6 nut and two metallic washers. Particularly, the composite specimen is a zero-degree unidirectional laminate fabricated in accordance with a standard hot-press process. The Young's Modulus along the fiber direction and density of the composite are 118 GPa and 1525 kg/m^3, respectively, calculated according to respective material properties of the fiber and matrix. The two composite joining components, both measuring 245×30×2.0 mm^3, were assembled with a lap length of 20 mm (bolt was positioned in the middle of the lap area) and a clamped length of 20 mm, as shown in **Figures 2** and **8**. The joint was tightened from 1 (fully loose) to 13 N·m (fully tightened).

All the measurement under a given bolt torque were repeated five times so that the influences of measurement errors and uncertainties can be minimized.

4.1 Experimental Set-up and Implementation

4.1.1 *VAM*-based Nonlinear Method

A shaker (B&K® 4809) was attached to the joint 39 mm from the free end to provide point-like excitation in terms of low-frequency pumping vibration. A piezo stack actuator (PI® P-885.11) was surface-mounted 39 mm from the bolt to provide high-frequency probing wave. Harmonic signals at f_L and f_H, defined as the low- and high-frequencies of excitations, respectively, were generated simultaneously using a two-channel waveform generator (HIOKI® 7075). The dynamic responses of the joint were captured using an accelerometer (B&K® 4393) and recorded using an oscilloscope (Agilent® DSO9064A) at a sampling frequency of 200 kHz. The photo of the experimental set-up is presented in **Figure 8(a)**.

f_L and f_H were prudently selected in order to achieve a maximum extent of *CAN* in a loose joint under a great degree of bolt loosening (1 N·m). To this end, a series of low-order natural frequencies of the joint was obtained using an impact excitation, as presented in **Figure 9(a)**. The ascertained natural frequencies were applied by the shaker to excite the joint, by doing which f_L was determined as the natural frequency leading to the most significant magnitudes of the second-order harmonics. A comparison among the spectra obtained at different natural frequencies, the frequency of 758 Hz was considered as the best candidate frequency for f_L, and consequently adopted in the following experiment. To determine an appropriate f_H, a white noise excitation was generated via the piezo stack actuator. The frequency responses of the joint were captured in a range between 9 and 16 kHz, and the frequency with the strongest response, termed as the *strongest natural frequency* (*SNF*) in this study, was ascertained. At *SNF*, *CAN* (*i.e.,* response magnitudes of sidebands) reaches its local maximum. As shown in **Figure 9(c),** 15.24 kHz was identified as *SNF* for the *C-C* joint and consequently selected as the excitation frequency of the probing wave in the experiment. The numerical excitation modes (at a frequency of 14.89 kHz) subject to the probing wave was set to be the same with those adopted in the experiment.

4.1.2 Elastic Wave-based Linear Method

The developed *VAM*-based detection framework was compared against elastic wave-based linear method using wave energy dissipation (*WED*) of guided Lamb waves. The *WED*-based linear method is proposed based on a premise that actual contact area of the partial interface in a joint increases with an augment in the applied torque and this consequently results in an increase in the transmitted energy of Lamb waves (*i.e.,* an decrease in the wave energy dissipation, *WED*) [30]. The sensitivity of sideband magnitudes to bolt loosening is further compared to that of propagating wave features, *i.e., WED* in what follows.

Two lead zirconate titanate (*PZT*) wafers, denoted by *PZT*1 and *PZT*2 respectively, were surface-mounted on the joint, 112.5 mm from the bolt. *PZT*1 served as the actuator, while *PZT*2 the sensor. A 7-cycle Hanning window-modulated sinusoidal tone-burst signal at a central frequency of 270 kHz was generated using a signal generator (NI® PXIe-1071), amplified with a high-frequency power amplifier (Ciprian® US-TXP-3) to 200 V (peek-to-peak), and then applied on *PZT*1, to introduce guided waves into the joint. The wave propagation, upon traversing the bolt, was monitored with *PZT*2 using an oscilloscope (Agilent® DSO9064A) at a sampling frequency of 20 MHz. The captured Lamb wave signals were averaged 64 times to minimize random measurement noise and uncertainties. The photo of the actual experimental set-up is presented in **Figure 8(b)**.

4.2 Results and Discussion

Representative experimental and numerical time-domain signals for the joint under *VAM*, when the bolt torque is 6 N·m, are presented in **Figure 10** and normalized with regard to the peak amplitude. The numerical signal was calculated under Scenario III, as an example. In simulation, the parameters ($\lambda_1^t, \lambda_1^r, \alpha$ and η) used in the enhanced theoretical model, as described by **Equations 4** and **5(b)** were determined when an accurate agreement between the experimental and numerical data is achieved regarding the natural frequencies of the first five vibration modes, as shown in **Figure 9(a).** While λ_2^t and λ_2^r in **Equation (4)**, were estimated by fitting the nonlinear experimental response (see **Figure 11(c)**) with using numerical results (see **Figure 6(f)**) calculated using Scenario III. The estimated (linear and nonlinear) parameters for the composite bolted joint are given in **Table 1**. The numerical excitation modes subject to pumping vibration and probing wave, calculated numerically by solving Equation (5a) using Newmark's method, were set to be the same with those adopted in the experiment, respectively.

In **Figure 10**, the two major frequency components are observed prominent which are corresponding to the pumping vibration and probing wave, respectively. A considerable similarity can be seen between the numerical and experimental data. Representative frequency responses of the joint in the *VAM* experiment with decreasing torques, *i.e.,* 13, 7 (fully tight) and 1 N·m (fully loose), are shown in **Figures 11 (a)** to **(c)**, from which the occurrence and increase of sideband magnitudes can be clearly observed adjacent to f_H. By comparing **Figures 11(a)** with **(b)**, conclusion can be drawn that at an early stage of bolt loosening (between 13 and 7 N·m), the variation in magnitudes of probing wave at f_H that is mainly associated with changes in linear dynamic responses is deemed as negligible. On the contrary, the variation of nonlinear responses in terms of changes in sideband magnitudes, although with a slight degree presented, is considered capable of distinguishing changes in bolt loosening degree. Furthermore, a comparison between **Figures 11(b)** and **(c)** argues that much sharper variations of both linear and nonlinear responses, *i.e.*, regarding signal magnitudes at f_H and at $f_H \pm f_L$, respectively, can be induced at a serious bolt loosening stage (*i.e.,* under the bolt torque range between 7 and 1 N·m).

Within the entire range of residual torques from 1 to 13 N·m, S_L and S_R were constructed based on **Equation (6)** at ten different bolt torque levels using experimental results, in which the scatter points and solid lines in **Figures 12(a)** and **(b)** signify separately measured results and their averaged values, respectively. From **Figures 12 (a)** to **(b)**, it can be clearly identified that an obvious change of curve tendency takes place at a certain point, probably between 6 and 7 N·m, below which the signal sensitivity to bolt loosening degree is much higher than that achieved beyond the point. Such an observation is consistent with the specific cases as presented in **Figures 11(a)-(c)**, implying that bolt loosening at an early stage is of much higher difficulty to be quantified than at a later stage. By recalling sideband variation achieved numerically, as shown in **Figures 7 (a)** and **(b)**, it is clear that Scenario III actually gives results much more consistent with the experimental findings. From such an aspect, it can be concluded that compared with Scenario II, the modified contact stiffness model (Scenario III) is more realistic and sensitive in both *CAN* characterization and bolt loosening identification.

To achieve a quantitative evaluation of the bolt loosening of the composite joint, a nonlinear bolt loosening indicator was defined [34] using both relative left and right sidebands, as

$$\beta = (S_L + S_R)/2. \quad \textbf{(7)}$$

For the purpose of comparison, the developed bolt loosening indicator in **Equation (7)** was further normalized according to

$$\beta^* = \beta - \beta_{ref}, \quad \textbf{(8)}$$

where β_{ref} denotes a reference indicator corresponding to the joint under the bolt torque of 1 N·m. In **Figure 13**, the experimental data are presented together with the numerical results, normalized using the averaged β. The overall decreasing tendency of the *VAM*-based indicator β^* sustains up to a considerably large level of bolt torque around 11 N·m, which means that the sensitivity of β^* is possible to be guaranteed in practical application at a quite early stage of the bolt loosening. It is clear that in **Figure 13** the numerical results corresponding to Scenario III show a considerably high consistency with the experimental results. Therefore, the decrease in the linear contact stiffness along with the increase in the nonlinear contact stiffness, induced by the occurrence and deterioration of bolt loosening, can lead to the augment in the sideband magnitudes. Consequently, the *VAM*-based indicator shows a considerable sensitivity to bolt loosening including the early stage.

As far as the comparison between *WED*- and *VAM*-based approaches is concerned, **Figure 14(a)**, as some representative results, shows a raw signal captured from the joint under a torque of 6 N·m, and **Figure 14(b)** exhibits the Fast Fourier Transform (*FFT*)-processed spectra of the signals traversing the mating parts of the joint under different torques. In the spectra, a wide range of the energy distribution from 200 to 320 kHz can be observed, which can be attributed to the dispersive and multimodal traits of Lamb waves propagating in the composite joint. Therefore, the linear bolt loosening indicator relied on *WED* was obtained by integrating response amplitude within the frequency range between 200 and 320 kHz in the frequency spectra, over which the signal possesses the majority of its energy. The reliance of the linear indicator on the residual torque of the joint is displayed in **Figure 15**. To observe the *WED*-based linear indicator augments drastically when the residual torque increasing from 1 (fully loosened) to 4 N·m, followed with a saturation afterwards. Such a monotonic trend can be attributed to the fact a greater applied torque naturally results in a larger interfacial area at the interface due to elastic deformation of asperities on the contact surfaces. The entire variation range of the linear indicator is less than 5 dB when the joint is tightened from 1 (fully loosened) to 13 N·m (fully tightened). While the entire variation range of the nonlinear indicator is observed larger than 15 dB. It is therefore that the *VAM*-based nonlinear indicator shows a higher sensitivity to bolt loosening of composite joints especially at the early loosening stage compared to the *WED*-based linear indicator.

5. Conclusions

In this study, contact acoustic nonlinearity (*CAN*) in *VAM*, induced by the "breathing" effect at the solid-to-solid interface of a bolted joint, is investigated analytically and experimentally, on which basis the *VAM*-inspired approach is developed to monitor bolt loosening in composite-composite (*C-C*) bolted joints. Numerical simulation based on the modified theoretical model with pressure-dependent nonlinear contact stiffness is implemented to facilitate the comprehending of generation mechanisms of *CAN* induced by a loose bolt and the dependence of nonlinear distortion, manifested as sidebands in the *VAM*-based method, on the residual torque of the loose joint. The numerical analysis has revealed that the decrease in the linear contact stiffness and increase in the nonlinear contact stiffness, induced by the decrease of residual torque of the loose composite joint, synergistically result in the augment of sideband magnitudes. Consequently, by developing the bolt loosening indicator using the sideband magnitudes, tightening state of the joint up to fully tightened state can be continuously identified with higher sensitivity compared to traditional *WED*-based linear method. The presented study provides a theoretical foundation, relying on which numerical analysis can be accurately conducted to facilitate the tasks of bolt loosening identification in a variety of structure types.

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