Evaluation of Bolt Loosening Using A Hybrid Approach Based on Contact Acoustic Nonlinearity

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Abstract. Bolted connections are widely used in various industrial sectors. Different loading conditions to which the connections are subjected can result in looseness of bolts, entailing timely detection to avoid system failure due to this. Linear ultrasonic inspection-based methods are currently the prevailing approaches in non-destructive evaluation (NDE) to serve this purpose. However these methods may lose their effectiveness when used to detect slight looseness of bolts. In this study, two nonlinear NDE approaches for detection of bolt loosening, using second harmonic nonlinearity of Lamb waves and vibro-acoustic modulation (VM), respectively, were developed. An analytical model based on Hertzian contact theory was proposed to establish a correlation between applied torques on a bolted joint and its contact acoustic nonlinear behaviours. These two approaches were validated experimentally by detecting bolt loosening in both metallic and composite connections. In the first approach, Lamb waves were introduced by a low-profile piezoceramic wafer, and an acoustic nonlinear parameter was calculated from the magnitude of extracted second harmonic of the Lamb waves; in the second approach, two harmonic excitations (i.e., a low-frequency vibration and a high-frequency probing wave) were produced by a shaker and a piezoceramic stack actuator, respectively, and the response sidebands were identified in spectra, to ascertain a modulation index. The variation of the nonlinear parameter and the modulation index, subjected to the torque applied on the bolt, has been found in a good agreement with theoretical prediction using the model. Results have demonstrated that the developed approaches are accurate, reliable and effective to detect bolt loosening at an early stage in a wide range of operational frequencies.

Introduction

Integration of multiple structural components via bolting connections is a prevailing assembling approach in manufacturing. Different loading conditions (e.g., shock and vibration) to which the connections are subjected can result in load creep and relaxation, which may lead to bolt loosening [1]. It is significant to detect bolt loosening at an early stage so as to prevent further system failure, enhance system reliability, and produce economic and human benefit.

Yang and Chang [2] proposed a linear acoustic method to identify the level of torque applied on a loosened bolt in a carbon-carbon composite thermal protection. Based on the damping of ultrasonic waves propagating in the structure, the looseness of the bolt was detected, and the results were promising in an elastic preload range. However, slight bolt loosening at an early stage, similar to a small-scale damage (e.g., fatigue damage), is not anticipated to induce evident changes in linear features extracted from ultrasonic waves [3], leading to deficiency of these linear acoustic approaches. Towards this, there has been an increased preference to use nonlinear acousto-ultrasonics-based approaches, with demonstrated effectiveness in characterizing fatigue damage. These approaches have a premise that when acoustic waves traverse the contact interface of the fatigue damage, the “breathing” motion pattern between two surfaces of the fatigue crack closes the gap during wave compression, while opens the gap in wave tension. The asymmetry in the contact restoring forces causes the stiffness parametric modulation, which introduces an additional localized nonlinearity — contact acoustic nonlinearity (CAN) — to the signals of ultrasonic waves guided by the medium [4]. By extending such a principle to detection of bolt loosening, it is feasible to predict the behaviour of a nonlinear contact configuration of a loosening bolt — a task difficult to be fulfilled using conventional linear techniques. Early applications of such nonlinear acoustic methods were represented by second harmonic-based approach. In this approach, when acoustic waves interact with the damage (e.g., debonding in composites) in the material or bolt loosening, the second harmonic waves are generated due to the nonlinear contact behaviour of the damage or bolts. Consequently, the magnitude of its amplitude of second harmonic could be used as an index to assess the health state of the structure. However, great efforts are required in practical implementation of these approaches, to minimize possible nonlinear distortion caused by transmitting/receiving devices as well as other instruments. On the other hand, the vibro-acoustic/impact modulation technique is another nonlinear acoustic method. In the method, a lower driving frequency “pumping” signal and another higher frequency “probing” signal are introduced into a structure simultaneously. When the monitored structure is intact, spectra of signal responses, in principle, exhibit two major frequency components only, corresponding to the pumping and probing signals, respectively. Otherwise, response signals contain additional sidebands in the spectra around the probing signal component, called left sideband (if lower than the frequency of probing signal) or right sideband (if higher than the frequency of probing signal). Meyer and Adams[5] made efforts to extend the applications of impact modulation (IM) from crack detection to assessment of bolted joints. The effectiveness of using the IM index to detect bolt loosening was demonstrated with both theoretical analysis and experimental investigation, although the detection range of bolt torques and the stability of acquired data are to be improved.

In recognition of the bottleneck of current scientific regime as addressed above, this study is dedicated to quantitative detection of bolt loosening in both aluminium and composite bolted joints, using second harmonic of Lamb waves and VM-based methods. This paper is organized as follows: firstly the source of nonlinearity in bolted joints when the connection interacts with acoustic waves is briefly discussed, based on which a simplified single-degree-of-freedom system is presented to establish a correlation between applied torques on a bolted joint and its contact acoustic nonlinear behaviours. Subsequently, the experimental investigation on the detection of bolted joints using the two nonlinear methods are presented. The results of both aluminium and composite (carbon fibre reinforced plate, CFRP) bolted joints are discussed.

1. Energy Dissipation-based Linear Methods

It is understandable that a preload P in a bolt introduced by a torque T applied on the bolt depends upon the bolt diameter d and friction coefficient K between the nut and bolt. To a first-order level of accuracy, this relation is written as [6]

$$P = \frac{T}{Kd}. \quad (1)$$

In practice, the contact surfaces of two beams, without loss of generality, are usually rough in the micro perspective (see Fig. 1).This leads to direct contact of partial interface only. To loosen a bolted joint can be treated as a process to decrease the pressure at the imperfect contact interface. To qualitatively describe the correlation between the applied torque and real contact area at the interface, a model based on Hertzian contact theory can be used. In the model, two elastic spherical bodies (radius R_1 and R_2) are squeezed together by a force P (see Fig. 1). The radius r of the contact region of the two spherical objects can be given as [7, 8]

$$r = [\frac{3}{4}\pi(k_1 + k_2)\frac{R_1 R_2}{R_1 + R_2}]^{1/3} P^{1/3}, \quad (2)$$

$$k_1 = \frac{1-\nu_1^2}{\pi E_1}, \quad k_2 = \frac{1-\nu_2^2}{\pi E_2}. \quad (3)$$

where E and ν are Young's modulus and Poisson ratio of contact material, respectively.

The real contact area S of the two spherical objects is

$$S = \pi r^2 = [\frac{3}{4}\pi^{5/2}(k_1 + k_2)\frac{R_1 R_2}{R_1 + R_2}]^{2/3} P^{2/3}. \quad (4)$$

From Eq. (4), it can be concluded that the real contact area is proportional to $P^{2/3}$. When Lamb waves traverse the contact region, part of the waves are leaked into another contact beam from a beam [5]. It is hypothesized that the amount of the wave leakage is proportional to the real contact area considering the fact that the wave leakage mainly happens in the real contact region. Then in an elastic range of contact material, the relation between applied torque and leaky energy (E_L) of a traversing Lamb wave could be written as

$$E_L \propto S \propto P^{2/3} \propto T^{2/3}. \quad (5)$$

Thus, the transmitted energy of incident Lamb wave is predicted to increase when applied torque increases. It should be noted that when the preload induced by the torque exceeds the elastic range of the contact material, the real contact area remains unchanged when applied torque continues increasing because of the occurrence of plastic deformation of the contact material, which may limit the sensitivity of a linear method towards detection of bolt loosening at the early stage.

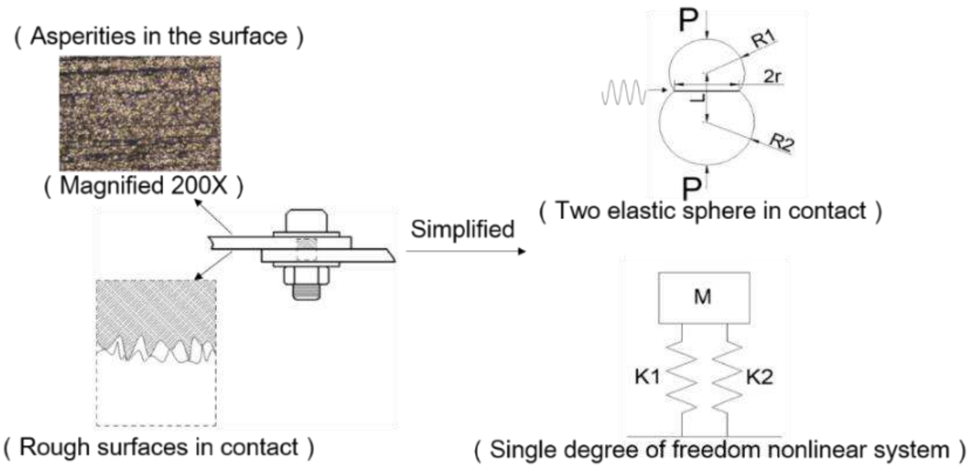

Fig. 1. Simplified model of rough surfaces in contact

2. CAN-based Methods

A simplified nonlinear model based on Hertzian contact theory is proposed to describe the relation between CAN of the bolted joint and torques applied on the bolt (see Fig. 1). In the absence of Lamb waves or vibration, the two surfaces of connecting joints are assumed to have an effective gap of X_0. Traversing of acoustic waves through the two surfaces results in a slight change X in the gap, and further in the contact pressure. Then the contact pressure p can be replaced by its Taylor series expansion near X_0 up to the second-order term, as

$$p(X+X_0) = p(X_0) - K_1 X + K_2 X^2. \tag{6}$$

The stiffness of the contact interface can be given as [7]

$$K_1 = -\left.\frac{dp}{dX}\right|_{X=0} = Cp^m \propto T^m, \tag{7}$$

$$K_2 = \frac{1}{2}\left.\frac{d^2 p}{dX^2}\right|_{X=0} = 0.5mC^2 p^{2m-1} \propto T^{2m-1}, \tag{8}$$

where K_1 is the linear stiffness and K_2 the second-order stiffness of the contact interface. C and m are two constants, which are related to the surface properties of the material in contact. It should be noted that in most cases, K_1 increases while K_2 decreases with an increase in p.

Based on CAN, two methods are developed theoretically and experimentally to detect bolt loosening in both metallic and composite connections.

2.1 *Method I:* Second Harmonic-based

2.1.1 Theoretical Interpretation

A single-degree-of-freedom system is established to describe the motion of the contact interface when it interacts with propagating Lamb waves (see Fig.1). In the model, the stiffness of the contact interface is treated as two springs with linear and nonlinear stiffness, which consists of pressure- and material roughness -dependent properties.

To take a step further, the external force applied on the contact interface introduced by the incident wave is assumed to be monochromatic. Then the equation of motions of the contact interface could be given as

$$M\ddot{x} + K_1 x - K_2 x^2 = F\cos\omega t, \tag{9}$$

where M is the assumed mass.

In order to obtain an explicit approximate solution to Eq. (9), based on the fact that K_2 represents a perturbation, it is convenient to rewrite Eq. (9) as

$$M\ddot{x} + K_1 x = \varepsilon K_2 x^2 + F\cos\omega t. \tag{10}$$

Then we can assume the solution to Eq. (10) to take the following form

$$x = x_1 + \varepsilon x_2, \tag{11}$$

x_1 and x_2 reflect the linear and second harmonic motion of the contact interface, respectively. Substituting Eqs. (11) to (10) and considering that the coefficients of ε on both sides of the equation are equal, the following differential equations are obtained as

$$M\ddot{x}_1 + K_1 x_1 = F\cos\omega t, \tag{12}$$

$$M\ddot{x}_2 + K_1 x_2 = K_2 x_1^2. \tag{13}$$

Neglecting the transient components, the solutions to Eqs. (12) and (13), corresponding to a steady-state oscillation, can be obtained as

$$x_1 = \frac{F}{K_1 - M\omega^2}\cos\omega t = B_1\cos\omega t, \tag{14}$$

$$x_2 = \frac{0.5K_2}{K_1 - 4M\omega^2} B_1^2 \cos 2\omega t = -B_2 \cos 2\omega t. \tag{15}$$

A parameter γ representing the acoustic nonlinearity is then defined as

$$\gamma = \frac{B_2}{B_1^2} = \frac{0.25mC^2 p_0^{2m-1}}{Cp_0^m - 4M\omega^2} \propto p_0^{m-1} \propto T^{m-1}. \tag{16}$$

Conclusions can be drawn that γ is dependent on the applied torque and surface properties of the contact interface. Notably, γ is theoretically predicted to decrease with an increase in the value of applied torque.

2.1.2 Experimental Validation

Two sets of beam-like connections, aluminium-aluminium measuring $245 \times 30 \times 2.8\,\mathrm{mm}^3$ and carbon-carbon measuring $190 \times 30 \times 1\,\mathrm{mm}^3$, were prepared. In each set, two beams were connected with a M6 bolt. The composite specimen (T700/7901 carbon-fibre-reinforced epoxy) has a stacking sequence of $[90, 0, 90, 0]_S$.

Two PZT wafers were attached to the surface of the beam with a distance of 40 mm in between (see Fig. 2). One wafer served as the wave actuator and the other served as sensor. A 16-cycle-Hanning-window-modulated sinusoidal signal centred at 320 kHz was generated (Agilent E8404A) and amplified with a high-frequency power amplifier (CIPRIAN US-TXP-3) to 200 V peek-to-peak amplitude. The signal captured by the PZT sensor was saved after averaged 64 times in an oscilloscope with a sampling frequency of 200 MHz, and finally processed in the MATLAB®.

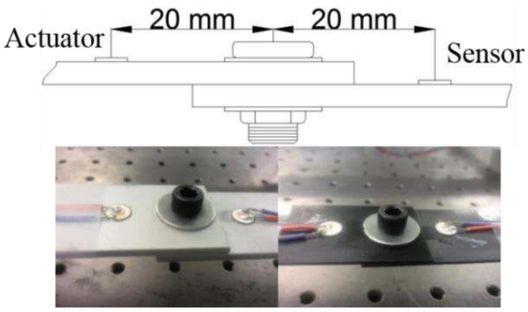

Fig. 2. Schematic of experimental setup for second harmonic method

Fourier transform was implemented to determine the shift of wave energy from the fundamental mode (A_1) to the second harmonic (A_2). If any abnormal increase of the energy related to higher-order harmonics in the wave signal traversing the bolt is detected, it can be concluded that such energy shift is due to the occurrence of bolt loosening. As a representative result, Fig.3 shows time-frequency spectra of signals captured in the case that applied torque is 5 Nm. The energy shifts from A_1 to A_2 are observed, indicating bolt loosening in the two types of connections.

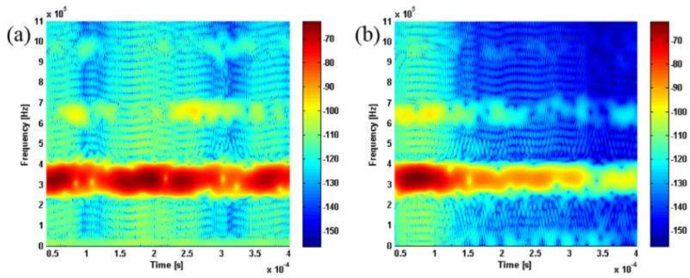

Fig. 3. Time-frequency spectra of loosened bolted joints with a torque of 5 Nm: (a) aluminum-aluminum; (b) carbon-carbon

Further, using a power spectral moment-based method[5], quantitative analysis on bolt loosening can be achieved by integrating the amplitude of fundamental (A_1) and second harmonic waves (A_2) in the frequency domain as follows

$$A_1 = \int_{f_1}^{f_2} W(f)df, \tag{17}$$

$$A_2 = \int_{f_3}^{f_4} W(f)df. \tag{18}$$

where f is the frequency variable, f_n (n= 1-4) is the integral range, and W the power spectral density (PSD) function.

From the spectra of the signals in Fig. 4, the energy of signals are found to dominate the frequency range of 300 kHz-340 kHz for A_1 and 620 kHz-660 kHz for A_2, respectively, which are chosen as the integral range to calculate the energy of A_1 and A_2 in Eqs. (17) and (18).

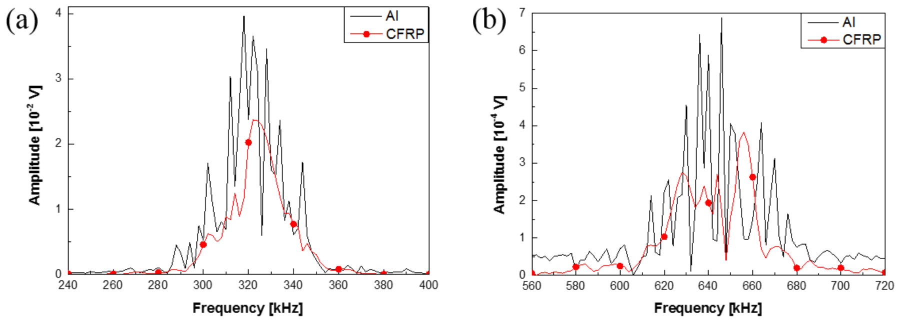

Fig. 4. Spectra of acquired Lamb waves passing through the bolted joint with a torque of 5 Nm: (a) fundamental mode; (b) second harmonic mode

It is noted that A_1 can be used as the equivalent linear transmitted energy to assess the state of bolted joints. On the other hand, an acoustic nonlinearity parameter β_S was further defined as

$$\beta_S = \frac{A_2}{A_1^2}. \tag{19}$$

Using Eqs. (17) and (19), A_1 and β_S for the two connections subjected to different applied torques are shown in Fig. 5.

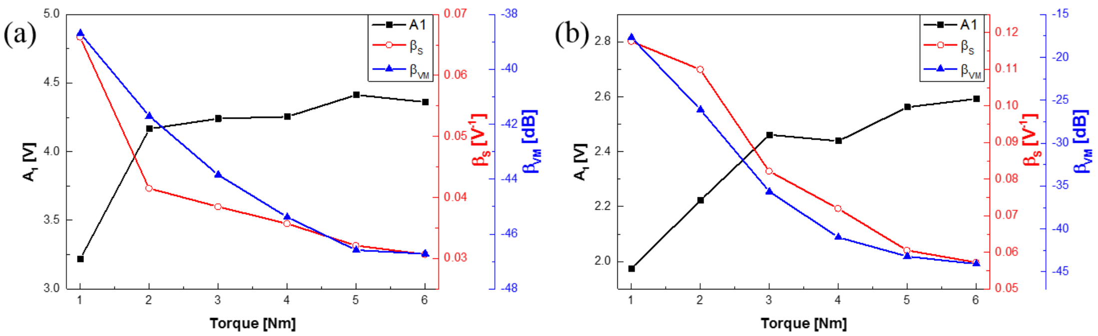

Fig. 5. A_1, β_S and β_{VM} vs different torques: (a) aluminum-aluminum; (b) carbon-carbon

2.2 *Method II: Vibro*-acoustic Modulation-based

2.2.1 Theoretical Interpretation

The single-degree-of-freedom system in Fig. 1 can also be used to derive the dependence of response amplitude of sidebands in signal spectra, on the applied torque and parameters of the two forces introduced by the pumping and probing signals. The equation of motions for the contact interface with two independent excitation forces is given as

$$M\ddot{x} + K_1 x - K_2 x^2 = F_1 \cos\omega_1 t + F_2 \cos\omega_2 t, \tag{20}$$

where ω_1 and ω_2 are the frequencies of probing and pumping signals, respectively. And F_1 and F_2 are the force amplitudes of these two signals, respectively. Using the perturbation method, Eq. (20) is rewritten as

$$M\ddot{x}_1 + K_1 x_1 = F_1 \cos\omega_1 t + F_2 \cos\omega_2 t, \tag{21}$$

$$M\ddot{x}_2 + K_1 x_2 = K_2 x_1^2. \tag{22}$$

Then one can obtain x_1 that satisfies the linear response of the contact interface, as

$$x_1 = G_1 \cos\omega_1 t + G_2 \cos\omega_2 t, \tag{23}$$

where G_1 and G_2 represent the linear dynamic response of the structure subjected to excitation forces F_1 and F_2, respectively..

Furthermore, the perturbation x_2 that reflects the second harmonic (at $2\omega_1$, $2\omega_2$) and sideband motion (at $\omega_1 \pm \omega_2$) is solved as

$$x_2 = \frac{G_1 G_2 K_2}{K_1 - M(\omega_1+\omega_2)^2}\cos(\omega_1+\omega_2)t + \frac{G_1 G_2 K_2}{K_1 - M(\omega_1-\omega_2)^2}\cos(\omega_1-\omega_2)t + \frac{0.5 G_1^2 K_2}{K_1 - 4M\omega_1^2}\cos(2\omega_1 t) + \frac{0.5 G_2^2 K_2}{K_1 - 4M\omega_2^2}\cos(2\omega_2 t). \tag{24}$$

It can be found that the response amplitude of the sideband is linearly proportional to the coefficient of nonlinearity, which is dependent on the surface properties of the contact interface and applied torque, similar to the conclusion drawn earlier in method I.

2.2.2 Experimental Validation

The VM-based (method II) method was comparatively recalled to detect bolt loosening in the same two sets of connections as second harmonic-based method (method I).

A piezo stack actuator (PI P-885.11), 39.17 mm away from the bolt, and a B&K4809 vibration shaker, 39.17 mm from the free end of the beam, were attached to the surface of the samples. The stack actuator and vibration shaker were used to produce the probing and pumping signals, respectively. A sinusoidal signal was generated by HIOKI 7075 waveform generator and amplified with a B&K power amplifier 2706 for the pumping signal. The signal was captured by B&K 4393 piezoelectric accelerometer with a distance of 35.83 mm from the bolt and saved in the oscilloscope with a sampling frequency of 200 kHz.

To select the excitation frequency for the pumping wave, an impact force was used to excite the bolted joint to obtain natural frequencies in the low orders. While for the probing wave, the local defect resonance (LDR) was ascertained with using a white noise to obtain the response spectrum of the structure [9]. After a series of trials, for the aluminium-aluminium bolted joint, the modes at 982 Hz and 14240 Hz were selected as the excitation frequencies of pumping and probing signals, respectively. While for the carbon-carbon bolted joint, 814 Hz and 13020 Hz were chosen, respectively. In the VM-based method, defects or loosening bolts generate additional signal components (sidebands) at the frequencies distinct from those originally transmitted. Consequently, the amplitude of sidebands only depends on the intensity of modulation and makes it fairly related to damage severity.

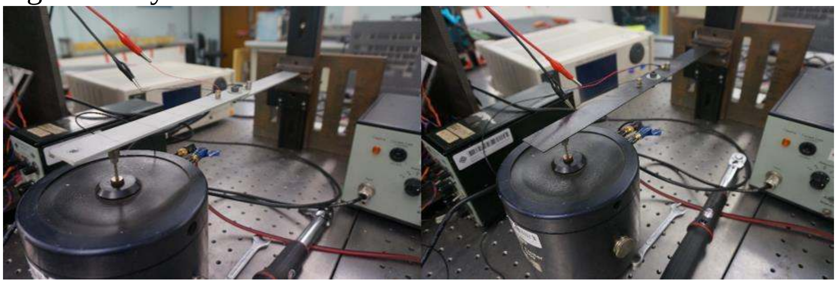

Fig. 6. Schematic of experimental setup for VM testing

The power spectra calculated from the response signals in the VM testing are shown in Fig.6. In order to quantify the modulation degree for bolted joints with different torques, the spectra are zoomed-in around the frequency of the probing signal.

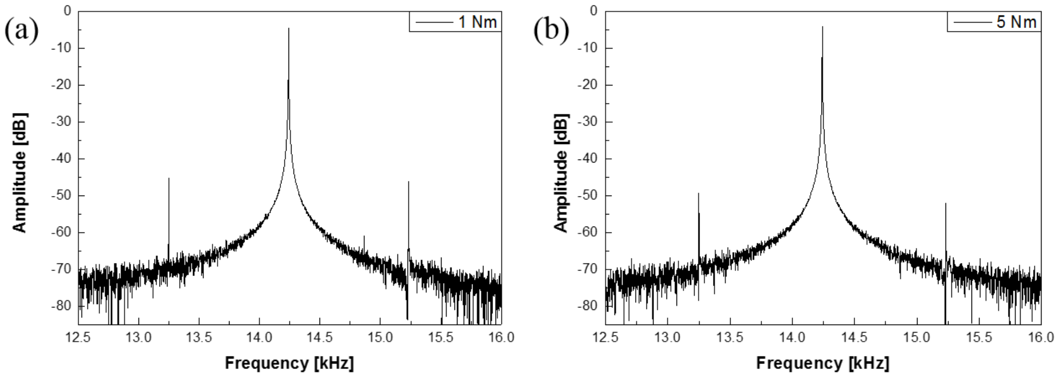

Fig. 7. Experimental power spectra of responses of aluminum-aluminum bolted joints under different torques

Obviously, the amplitudes of sidebands exhibit a fair correlation to the preload loss in the bolted joints, where it decreases with an increase in the value of applied torque. In order to quantify the effect of applied torque on the amplitude of sidebands, a nonlinear modulation index β_{VM} was defined as

$$\beta_{VM} = (A_L + A_R)/2 - A_H. \tag{25}$$

where $A_{L/R}$ and A_H are the amplitudes (in the unit of dB) of left, right sideband and probing signal respectively.

Using Eq. (25), β_{VM} for the two connections subjected to different applied torques are shown in Fig. 5.

3. Results and Discussion

A_1 in the linear method, β_S in the second harmonic-based method, and β_{VM} in the VM-based method were used to assess the state of bolted joints, respectively. In the Fig. 5(a), it could be seen that A_1 for aluminum specimen increases drastically from 1 Nm to 2 Nm, after which it stabilizes despite of any further increase in the preload. This is because that a small portion of interface is actually in contact when the preload is small (1 Nm) and most of Lamb waves dissipate in the gap between the interface. However, when the preload increases subsequently, a larger portion of interface comes to contact, which results in more energy of Lamb waves passing through the bolt. Beyond 2 Nm torque, contact area experiences slight change as the preload increasing, therefore transmission of Lamb waves through the bolted joints remains stable. For the second harmonic-based method, β_S decreases drastically from 1

Nm to 2 Nm and then decreased stably until the preload reached 6 Nm. Finally, for VM-based method, β_{VM} decreases stably from 1 Nm to 5 Nm, after then it experiences slight change. On the other hand, composite specimen shares the similar variation trend in A_1, β_S and β_{VM} as their respective counterparts in the aluminum-aluminum connection (see Fig.5 (b)). From the comparison between the results obtained using different methods, it could be found that CAN-based methods demonstrate higher sensitivity on the detection of bolt loosening at the early stage than the linear acoustic method. Notably, effectiveness of these two methods is not dependent on connecting material.

4. Conclusion

In this paper, quantitative identification of bolt loosening was presented using the nonlinear NDE methods. For the second harmonic-based method, the CAN of bolted joints with different applied torques were calculated from the amplitudes of fundamental mode and the second harmonic of captured signals to identify bolt loosening. This method shows its efficiency in both metallic and composite connections, but it entails subsequent data processing such as integration of the response amplitude. To avoid the data processing and minimize the influence of non-damage related nonlinearity included in the signal, VM-based method was conducted on the same bolted joint. Such a method demonstrates higher sensitivity in the detection of bolt loosening compared with second harmonic-based method. This work can further facilitate development of an SHM approach to monitor bolt loosening accurately, sensitively and reliably in a wide range of operational frequency without the limitation of the connecting material.

Acknowledgments

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