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Continuous Monitoring of Tightening Condition of Single-lap Bolted Composite Joints Using Intrinsic Mode Functions of Acoustic Emission Signals：A Proof -of -concept Study

Zhen ZHANG [a, b], Yi XIAO [a]*, Zhongqing SU [b] and Yongdong PAN [a]

[a] School of Aerospace Engineering and Applied Mechanics,

Tongji University, Shanghai 200092, P.R. China

[b] Department of Mechanical Engineering,

The Hong Kong Polytechnic University, Hong Kong SAR

* Author to whom correspondence should be addressed. E-mail: y_xiao@tongji.edu.cn

Abstract

Intrinsic mode functions (*IMF*s) of acoustic emission (*AE*) signals, extracted from signals using empirical mode decomposition (*EMD*), were used to characterize the contact conditions of asperities (e.g., sliding friction or collision) in the mating parts of bolted composite joints undergone flexural vibration, whereby to evaluate the tightening condition of the joints quantitatively. Specifically, the sliding friction-related *IMF*s, generated in the mating parts of the two joining composite components (termed as *C*-*C* contact) were ascertained from those generated from the contacts between the joining components and metallic fasteners (termed as *M*-*C* contact), via a Hilbert-Huang transform (*HHT*). Subsequently, the *C*-*C* contact-related *IMF*s were linked to the contact behaviors of asperities at the joining interfaces, reflecting quantitatively the degree of the residual torque of the bolted joints. The fatigue performance of the joints was further evaluated according to the changes in the energy ratios of the *C*-*C* contact-related *IMF*s. Experimental Results have revealed that the gross energy of *AE* signals is capable of evaluating the residual torque of the joints within a limited range. Vibration loosening of composite joints was found to result in an increase in the energy ratios of *C*-*C* contact-related high-frequency *IMF*s, on which basis the detectability of the *AE*-based structural health monitoring is further improved, making it possible to evaluate the tightening condition of a bolted joint when the joint undergoes vibration fatigue. This proof-of-concept study provides a promising solution to evaluate the contact conditions of bolted composite joints during assembly and to continuously monitor the tightening condition throughout the service life of the joints using the *AE* technique.

***Keywords*:** bolted composite joint; bolt loosening; intrinsic mode function; acoustic emission; structural health monitoring

1. Introduction

Past decades have witnessed an increasing use of advanced composite materials in engineering structures, due to their superior mechanical properties compared with traditional metallic materials such as high specific stiffness and strength[1, 2], along with outstanding resistance to fatigue and corrosion. In order to meet the demand of design and maintenance, integration of multiple primary components via bolted joints is a prevailing assembling approach for composite structures[3]. However, during the service lives of bolted composite structures, various factors[4], for instance improper bolt preload (*i.e.,* applied torque), high temperature and humidity environment, and dynamic loading, have the potential to initiate and accelerate the process of bolt loosening. Among them, the applied torque plays a critical role in determining the durability and damage tolerance of bolted joints[2, 5-7]. Most failures of bolted joints were reported to be caused by metallurgical fatigue, under-tightening, over-tightening and irregular tightening of the bolts. If the applied torque is insufficient, all external loads are to be transferred by the bolt, which results in excessive fluctuating stress when the bolted joint is subject to dynamic loading. On the other hand, an excessive preload produces an overlarge and noncyclic tensile load in the bolt, as well as a high mean stress in the mating area, which exceeds the endurance limits of the joint materials [8]. Therefore, improper preload (*i.e.,* too high or too low) potentially leads to failure of the bolted joint.

To guarantee the performance of a bolted joint, it is critically important to develop efficient methods to characterize the contact conditions during assembly and further surveil the tightening condition throughout its service life. In order to serve these purposes, varied active and passive acoustic methods relying on structural health monitoring (*SHM*) techniques [9-11] have been developed to monitor the loosening of bolted structures. In the active acoustic methods, either linear signal features (*e.g.,* wave energy dissipation, delay in time-of-flight[12, 13], wave reflection/transmission[3]), or nonlinear signal features (*e.g.*, generation of high-order harmonics [14-16] and modulation sidebands[3]) have been adopted to identify a loose bolt. In the passive acoustic methods, *AE* signals can be used to interpret the details of physical processes occurring in the monitored structure, including contact behaviors in the mating parts of a bolted joint[17, 18]. When a bolted joint is subject to dynamic loading, the mating parts at the contact interface, of which surfaces are uneven with randomly distributed asperities in the micro perspective, undergo a slight relative motion. The asperities on the two contact surfaces, applied with different degrees of pressure, exhibit certain type of contact behavior, for example asperity collision, elastic and plastic deformation, or fretting wear (*i.e.,* formation and rupture of adhesion junctions) [19-21]. It was reported that specific contact behavior at the contact interface can be identified using pattern recognition and frequency analysis of *AE* signals [19, 20], which have demonstrated their efficiency in characterizing failure modes of carbon fiber reinforced plastics (*CFRP*) (*e.g.,* matrix cracking, fiber pull-out and breakage, and debonding). Therefore, it is potential to surveil the tightening condition of a bolted joint subject to dynamic loading (*i.e.,* flexural vibration) by means of signal analysis on the *AE* signals generated from asperity contacts at the interface. However, traditional time-frequency analysis (*e.g.,* short-time Fourier transform, *STFT*) may result in false information when applied to process non-stationary or nonlinear mechanical fault signals (*e.g., AE* signals) [22-24]. In this backdrop, empirical mode decomposition (*EMD*) has been widely studied and applied in various *SHM* fields (*e.g.,* damage detection[22], pattern recognition [23] and system identification, *etc.*). When a signal is dealt with *EMD*, a set of complete and almost orthogonal components (*i.e.,* intrinsic mode functions, *IMF*s) can be obtained, which represent the natural oscillatory modes in the original signal, and are determined by the characteristics of the signal itself. Hilbert-Huang transform (*HHT*) spectrum of the *IMF*s further obtained by using Hilbert transform provides accurate time-frequency signal characteristics.

In this study, *AE* signals induced by contacts of asperities at the *C-C* and *M-C* interfaces in the bolted composite joint were recognized using the *HHT*-processed characteristics of *AE* signals. Firstly, single type *AE* signals generated from asperity contacts at the two distinct types of contact interfaces were captured and processed respectively by *HHT* to ascertain the time-frequency characteristics of decomposed *IMF*s. Subsequently, these *IMF*s were used as basic functions to recognize the *C-C* contact related *IMF*s in the mixed *AE* signals from a bolted composite joint, by comparing the signal time-domain waveform and time-frequency distribution in the *HHT* spectrum. With usage of energy ratios of the *C-C* contact-related *IMF*s, contact conditions of the bolted joint under different applied torques subject to flexural vibration were evaluated by the *AE* signals. On this basis, tightening conditions of the bolted composite joints under different torques subject to vibration fatigue were continuously monitored through decrease of compressive strain of the bolts and changes in the energy ratios of the *C-C* contact-related *IMF*s of the *AE* signals.

2. Hilbert-Huang Transform (*HHT*) for Bolt Loosening-induced *AE* Signals

In a bolted composite joint, there exists a series of contact interfaces as shown in **Figure 1(a)** (*e.g.,* interfaces between metallic washer and composite beam (*M-C*) and interfaces between two composite components (*C-C*)), of which surfaces are rough with randomly distributed asperities. As a representative result, the microstructure of the surface of the composite specimen was obtained by scanning electron microscopy (*SEM*) and displayed in **Figure 1(b)**. To observe that asperities of different sizes distribute on the nominally flat surface and consequently when the two composite beams are assembled by a bolt, the interface in the mating parts features partial contact as illustrated in **Figure 1(c)**.

In practice, mixed *AE* signals produced by asperity contacts at both the *M-C* and *C-C* interfaces in the joint generate when the joint is subject to dynamic loading. In what follows, asperity contacts at these two interfaces will be characterized by respectively using time-frequency analysis on the related single type *AE* signal. In addition, signal features of *AE* signals generated from asperity contacts at the *C-C* interface under increasing applied pressure are to be further studied by comparing the frequency distribution. Previous studies [20, 21] confirmed that contacts of asperities in larger contact area (induced by greater applied pressure) produce *AE* signals with longer durations (*i.e.,* lower centered frequencies) through both experimental investigation and numerical simulation. On this basis, taking the *C-C* interface as an example, three representative types of asperity contacts are discussed to facilitate the understanding of generation mechanisms of *AE* signals in a bolted composite joint by considering the influence of residual torque on the signal characteristics. When the bolt is fastened, as shown in **Figure 1(c)**, the largest asperities (Mode I) on the surfaces firstly come into contact and undergo intensive deformation, the moderate asperities (Mode II) are in a weak contact and slight gaps exists between the smallest asperities (Mode III). Once a relative motion between the contact surfaces presents, sliding friction occurs between both the Mode II and Mode I asperities but with different contact durations, which are determined by the substantial contact area of the asperities. The Mode I asperities carry a larger contact force and consequently a higher degree of deformation presents, leading to a larger substantial contact area. As a result, *AE* signals with a longer duration (*i.e.,* a lower centered frequency) are generated. Conversely, shorter-duration *AE* signals (*i.e.,* with a higher centered frequency) generate from the contacts between the Mode II asperities. If sliding distance of the two surfaces exceeds the gap between the Mode III asperities, Mode III asperities on one contact surface attempt to slide past those on the opposite surface, which results in the collision contact behavior and generates *AE* signals with the shortest duration. With increasing applied torque, for larger asperities in real contact (Mode II and Mode III), elastic and plastic friction (see **Figure 1(d)**) occurs sequentially. Once the asperities are overloaded, wear produces consequently at the contact interface.

To conclude that the contacts between the three types of asperities naturally generate *AE* signals with distinct characteristics in terms of time durations and centered frequencies. Upon the occurrence of bolt loosening in a bolted composite joint, a reduce in contact area between asperities, caused by the decrease in contact pressure, results in more frequency components with higher centered frequencies in the *AE* signals[21]. With usage of empirical mode decomposition (*EMD*), the *AE* signals can be broken down into various components (*IMF*s) with decreasing centered frequencies, which can be correlated with the contact behaviors of the asperities and further evaluate the tightening condition of the bolted joint.

The signal processing procedure of *EMD* method is illustrated in **Figure 2**. In the process of applying *EMD* to an *AE* signal *X(t)*, the upper and lower envelops of the signal are firstly obtained by connecting local maxima and minima using a cubic spline function, respectively.

The mean of the upper and lower envelopes is then obtained and signified as m_{11}, and the first 'Proto-Intrinsic Mode Function' (h_{11}) is defined as

$$X(t) - m_{11} = h_{11} \quad \textbf{(1)}$$

In the subsequent processes, h_{11} is treated as the new original signal and m_{12} is obtained by averaging the upper and lower envelopes of h_{11}. Then the second 'Proto-Intrinsic Mode Function' (h_{12}) is obtained as

$$h_{11} - m_{12} = h_{12} \quad \textbf{(2)}$$

The above process (*i.e.*, sifting process) is repeated k times until h_{1k} becomes the first *IMF* (C_1) with the highest centered frequency, which satisfies two conditions: (1) in the whole data set, the number of extrema and the number of zero crossings must either equal or differ at most by one; and (2) at any point, the mean value of the envelope fitted by the local maxima and the envelope fitted by the local minima is zero.

$$C_1 = h_{1k} \tag{3}$$

According to above description of generation mechanisms of *AE* signals, the first *IMF* (C_1) is deduced to be associated with asperity contacts with the shortest contact duration (*i.e.,* the highest centered frequency). The difference between $X(t)$ and C_1 is defined as the first residue r_1

$$X(t) - C_1 = r_1 \tag{4}$$

The sifting process is repeated to obtain all *IMF*s, with decreasing centered frequencies, of the *AE* signal.

$$r_1 - C_2 = r_2 \tag{5}$$

$$\cdots$$

$$r_{n\text{-}1} - C_n = r_n \tag{6}$$

The decomposition procedure ends once the residue r_n , becomes a constant, a monotonic function, or a function with only one maximum and one minimum. Finally, the *AE* signal $X(t)$ can be expressed with a sum of decomposed *IMF*s and the residue, as

$$X(t) = \sum_{j=1}^{n} C_j + r_n \tag{7}$$

Hilbert transform is subsequently performed on the decomposed *IMF*s to conduct time frequency analysis of the signal, which is defined as

$$H(t)=\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{C_j}{t-t'}dt'. \tag{8}$$

Then analytic signal $Z(t)$ whose real part is C_j and the imaginary part is its Hilbert transform $H(t)$ can be constructed as

$$Z(t)=C_j+iH(t)=e(t)e^{i\phi(t)}. \tag{9}$$

The envelope $e(t)$ and instantaneous phase $\phi(t)$ can be written as

$$e(t)=\sqrt{C_j^2+H^2(t)},\ \ \phi(t)=\arctan\frac{H(t)}{C_j}. \tag{10}$$

The decomposed *IMF*s with decreasing centered frequencies will be linked to the contact behaviors of the asperities at the interfaces of the loose joint and further used to evaluate the residual torque in what follows.

3. Specimen Preparation and Experimental Setup

In this study, single type *AE* signals generated from asperity contacts at both *C-C* and *M-C* interfaces were firstly captured and processed respectively by *HHT* to ascertain frequency distribution of decomposed *IMFs* from these two different interfaces. Subsequently, the *IMFs* generated from the single-type interface were used to recognize the *C-C* contact related *IMFs* in the mixed *AE* signals from a bolted composite joint. The above-mentioned research flowchart is displayed in **Figure 3**.

To validate the efficiency of *IMFs* in identifying contact conditions of joint interfaces, three sets of experimental setups were used to capture *AE* signals generated at the single-type contact interface (*i.e., C-C* contact in two assembled composite beams as displayed in **Figure 4(a)** and *M-C* contact in a bolted beam as shown in **Figure 4(b)**) and mixed-type contact interface (in a bolted composite joint (see **Figure 4(c)**)). Note that composite beams were cut from sheets of laminated T700/7901 carbon-fiber-reinforced epoxy, obtained by using hot pressing with a stacking sequence [90, 0, 90, 0]s. Specimens were 1mm thick and 30 mm wide.

To generate *AE* signals from *C-C* contact, in **Figure 4(a)**, two composite beams, with lengths of 100 mm and 190 mm, respectively, were assembled with an overlap length of 20 mm by using insulation tape. One end of the beam was secured to the moving element of a vibration table (ES-3-150) with an M8 bolt. A sealant was used to avoid *AE* source from contacts between the M8 bolt and other components. The beam in the length of 100 mm without the assembled beam (190 mm) was firstly excited to ascertain that *AE* signals from contacts between the M8 bolt and other components were eliminated. The specimens were shaken vertically with a displacement of 0.6 mm at a frequency of 22.3 Hz by using the sinusoidal motion of the moving element and were monitored with an acceleration sensor. A four-channel SAEU2S *AE* system (Soundwel Co.) was employed to capture *AE* signals generated from the two assembled composite beams (*i.e., C-C* contact) subject to vibration in a short time (*i.e.,* 8 seconds), using an SR 150M sensor with a wide resonant frequency range between 10 and 160 kHz as shown in **Figure 5**. The *AE* signals were recorded at a sampling frequency of 2 MHz. A threshold of 40 dB was used to avoid involvement of environmental noise and boundary reflections in the captured signals. To simplify the analysis, acoustic wave attenuation and multiple boundary reflections were believed consistent before and after the fatigue, given the *AE* sensor position and sample boundary were the same. Multiple reflections from edges and core of the joints were minimized by setting proper threshold value (40 dB) and hit interval (300 μs). Most multiple reflections were captured as separated signals (achieved by hit interval) but filtered due to low energy (achieved by threshold), which was caused by attenuation characteristics of *AE* signals propagating in composites.

To generate *AE* signals from *M-C* contact (*i.e.,* contact between the metallic fasteners and the composite beam), as shown in **Figure 4(b)**, an intact beam with a length of 270 mm was drilled a thread hole and assembled with an M6 bolt after confirming that *AE* signals from contacts between the M8 bolt and other components were eliminated. The M6 bolt was tightened from 1 to 9 N·m, with an increasing step of 1 N·m, so as to collect *AE* signals produced from the *M-C* contact in each scenario. The *AE* signals were collected when the specimens were under the same excitation condition as those shown in **Figure 4(a).**

To obtain the *AE* signals generated from the mixed-type contact (including both *C-C* and *M-C* contacts), as depicted in **Figure 4(c)**, the same beams as those shown in **Figure 4(a)** were assembled with an M6 bolt to form a bolted composite joint. The joint was tightened from 1 to 9 N·m and excited under each torque using the same excitation conditions as those shown in **Figures 4(a)** and **(b)** in a short time (*i.e.*, 8 seconds).

To verify the efficiency of the *HHT*-processed *AE* signals in the continuously monitoring of vibration loosening of the bolted composite joints, four bolted joints with the same geometry as that in **Figure 4(c)** but applied with different torques (*i.e.,* 3, 5, 7 and 9 N·m), as displayed in **Figure 4(d)**, were fatigued for 10 hours (fatigue experiments were repeated three times). The specimens were shaken vertically with a displacement of 0.6 mm at a frequency of 22.3 Hz by using the sinusoidal motion of the moving element. The detail procedure for the fatigue experiment can be found in our previous research [4]. During the vibration fatigue, the *AE* signals and compressive strain of the bolt (indicating the residual torque), were continuously registered in the *AE* device and strain indicator, respectively.

4. Results and Discussions

4.1. Characterization of the Residual Torque of Bolted Composite Joints

To achieve a quantitative monitoring of bolt torque using the mixed *AE* signals generated from both *C-C* and *M-C* interfaces in a bolted composite joint, unique characteristics and quantitative dependence of these two signals on the applied torque must be firstly understood. Motivated by this, *AE* signals generated at the single-type contact interface (*i.e., C-C* contact as shown in **Figure 4(a)** and *M-C* contact as shown in **Figure 4(b)**) are processed with *HHT* and the decomposed *IMF*s are comparably studied to ascertain their distinct characteristics in this section.

The original *AE* signal (the average of 300 signals) and its first four *IMF*s, generated from the *C-C* contact between the two composite beams assembled by insulation tape (see **Figure 4(a)**), are displayed in **Figures 6** and **7**, respectively. The first four *IMF*s in **Figure 7** are observed to possess increasing periods. Time frequency analysis on the original signal were comparably conducted by using short-time Fourier transform (window length:128, overlap number: 127, *FFT* length:1024) and Hilbert-Huang transform and the corresponding spectra are displayed in **Figures 8(a)** and **(b)**, respectively. The main energy of the *AE* signal is observed to distribute in the frequency range between 20 and 200 kHz. From further observation, a higher time-frequency resolution is observed in the *HHT* spectrum presented with normalized energy compared to the former one.

Figures 9(a) and **(b)** show the time-presentation of the original *AE* signal (the average of 300 signals) and its first *IMF* generated from the bolted beam (*i.e., M-C* contact, see **Figure 4(b)**) under 1 and 7 N·m, respectively. Noted that C_i^T denotes the i^{th} *IMF* of the *AE* signals generated from specimens under a torque of *T*. From the comparison with regards to signal envelopes in the time domain, a high similarity can be found between the original signal and its first *IMF*, which means the first *IMF* dominates the energy of the original signal. The *HHT* spectra presented with normalized energy of the two signals in **Figure 9** are comparatively shown in **Figures 10(a)** and **(b)**. To observe the main frequency components of the *AE* signals generated from the *M-C* contact distribute between 10 and 40 kHz, regardless of applied torque. Marginal spectra of the *AE* signals captured from the bolted beam (*M-C* contact) under different torques are shown in **Figure 10(c)**, in which the energy ratio of low-frequency components (below 25 kHz) is observed larger with the increase of applied torque. In addition, a clear frequency shift shows when applied torque decreases. This phenomenon is consistent with previous analysis (Section 2) in terms of the influence of applied torque on the asperity contacts and resultant *AE* signal characteristics. To be more specially, a high pressure increases the contact area of asperities and consequently more *IMF*s with longer durations (*i.e.,* low centered frequencies) occurs. It is noteworthy that when the bolt was tightened to 8 N·m or more, no *AE* signals were captured. This is because that no obvious relative motion at the *M-C* interface occurs when the applied torque reaches 8 N·m, which introduces a high pressure at the interface between the metallic washer and the composite beam (*i.e., M-C* interface). It also indicates that *AE* source from the contacts between the M8 bolt and other components was circumvented successfully.

Comparing the *AE* signals generated from the *M-C* contact to those generated from the *C-C* contact, it is found that the *M-C* contact generates the *AE* signals dominating the frequency range between 10 and 40 kHz, while the *AE* signals induced by the *C-C* contact mainly distribute between 20 and 200 kHz. The difference in roughness and hardness between metal and resin is responsible for the diversity of their frequency distribution. Such frequency distribution difference can be used to characterize *AE* signals generated from *M-C* and *C-C* contact and provide a basis to extract *C-C* related *IMF*s from the mixed *AE* signals.

The typical amplitude distribution (gross energy) of the mixed *AE* signals generated in a bolted composite joint during vibration is shown in **Figure 11(a)**, and **Figure 11(b)** is the averaged results of three repeated tests. To observe that in **Figure 11(a)** when the applied torque is 3 N·m, the amplitude of the *AE* signals distributes over a wide range, which indicates uncontrolled contact behaviors in the bolted joint arising from a lack of sufficient pressure on the contact surfaces. Similar phenomena present when the torque is 1 and 2 N·m, which are not to be discussed in detail. When the applied torque continues increasing, the amplitude of the *AE* signals reaches a steady value, especially for the joint under 7 N·m. From the averaged results as displayed in **Figure 11(b)**, a monotonic decrease in the signal amplitude is observed until the applied torque reaches 7 N·m. After then, it increases slightly until 9 N·m. Damage caused by intensive pressure on the composite surface below the outer border of the washer was found in the further observation. Therefore, *AE* signals induced by the surface damage are inferred to cause the increase of signal amplitude (*i.e.,* gross energy) after the torque exceeds 7 N·m. According to our previous analysis as displayed in **Figure 1(d)**, the joint applied with the torque between 3 and 6 N·m is insufficiently tightened (I_t condition) when most asperities under elastic deformation. Under the torque of 7 and 8 N·m, the jointed is considered as efficiently tightened (E-t condition). When the applied torque exceeds 8 N·m, intensive pressure causes surface damage at the interfaces and consequently the joint is over-tightened (O-t conditions). From **Figure 11**, it can be concluded that the detectable range regarding bolt loosening is limited from 4 to 7 N·m with the usage of gross energy of *AE* signals.

To further improve the detection range of bolt loosening using *AE* technology, in the following section intrinsic mode functions of the same *AE* signals as shown in **Figure 11(b)** will be further extracted using empirical mode decomposition and correlated to the contact conditions of the joining interfaces.

The *AE* signals (averages of 300 signals) generated in the bolted joint under 3 and 7 N·m were comparatively processed with *HHT* and their *IMF*s (C_i^T) in time-domain are shown in **Figures 12** and **13**, respectively. In **Figure 12**, the first three *IMF*s (*i.e.*, C_1^3, C_2^3 and C_3^3) decomposed from the *AE* signal generated from the bolted joint under a torque of 3 N·m, are found to be similar with C_1, C_2 and C_3 in **Figure 7**. In addition, from further observation on the results from joint under 7 N·m, the periods of the *IMF*s are observed to increase when the joint was applied with augmenting torques. To investigate energy shift in the signals generated from the joint under increasing torque (from 1 to 9 N·m), *HHT* spectra of the signals (first four *IMF*s) are comparably displayed in **Figure 14**. The first three *IMF*s are observed to distribute in the frequency range larger than 40 kHz and show a high sensitivity to changes in the applied torque. Strong *IMF*s with frequencies of around 160 kHz are only found for the inefficiently tightened joints (1 and 3 N·m). In addition, high-frequency *IMF*s decrease with the increasing torque applied on the joint, which is similar with results in the bolted beam. Through the comparison with signals generated from the single-type *C-C* and *M-C* contacts in terms of *HHT* spectra, the first three *IMF*s of the mixed signals captured from the bolted composite joint are inferred to be produced by the *C-C* contact.

To achieve a quantitative analysis of tightening conditions of bolted composite joint using *AE* signals, energy ratio (R_j) of each *IMF* C_j is calculated using the following equation

$$R_j = E(C_j) / \sum_{j=1}^{n} E(C_j) \times 100\% . \quad \textbf{(11)}$$

where $E(C_j)$ is the equivalent energy of *IMF* C_j , obtained by accumulating the squares of signal amplitudes of C_j in the time domain. The energy ratios of the first three *IMF*s and their summation ($R_{1\text{-}3}$) along with the ratio of residual *IMF*s ($R_{Residual}$) of the mixed *AE* signals are obtained and displayed in **Figure 15**. R_2 and R_3 are found to decrease when the torque applied on the bolt increases from 4 to 9 N·m, while an observable increase presents in R_1 when the torque increases to 9 from 8 N·m, which is inferred to be correlated to the surface damage as mentioned above. With the usage of $R_{Residual}$ and $R_{1\text{-}3}$, changes of bolt torque in the range between 4 and 9 N·m can be detected. The *HHT*-processed characteristics of *AE* signal show a better sensitivity to early bolt loosening compared to amplitude-dependent *AE* technology as shown in **Figure 11(b)**.

4.2. Monitoring of Vibration Loosening of Bolted Composite Joints

In Section 4.1, *HHT*-processed *AE* signal characteristics show the sensitivity to changes in the bolt torque manifest as energy shift form low-frequency components to high-frequency components with decreasing torque. The efficiency of the proposed method in detecting bolt loosening of composite joints during vibration fatigue will be further verified in what follows.

During the vibration fatigue, fretting wear occurs at the contact interfaces in composite joints due to dynamic external loading, as shown in **Figure 16**. Such volume loss at the contact interface leads to bolt loosening at the early stage of vibration fatigue. From previous analysis in Section 2, it can be concluded that the decrease in bolt torque results in a reduce in the interfacial pressure and an augment in the sliding distance between contact surfaces. As a consequence, more asperities with relative small sizes feature weak contacts and produce more high-frequency *IMF*s in the *AE* signals. To validate the efficiency of the proposed *AE* method in the continuous monitoring of bolt loosening, in this section four bolted composite joints (**see Figure 4 (d)**) under 3, 5, 7 and 9 N·m are fatigued using flexural vibration for 10 hours simultaneously and monitored by using the *HHT*-based characteristics of *AE* signals. Most *AE* signals were captured during the first two hours, indicating intensive fretting wear at the interfaces present at the early fatigue stage. Therefore, fatigue experiment in the first two hours will be discussed in detail. The accumulated energy of the original *AE* signals generated in the four joints and the changes in the compressive strain of the bolts are plotted over time in **Figures 17(a)** and **(b)**, respectively. The slope of the energy curves represents energy release rate of asperity contacts, which can be used to indicate the stability of the bolted joints under fatigue. From **Figure 17(a)**, it can be found that the *AE* signals generated in the bolted joint under 3 N·m exhibit most frequent changes in the energy release rate. While the *AE* signals generated in the bolted joint under 7 N·m exhibit a relative low energy release rate, which indicates a stable contact condition of the bolted joint under this torque. However, cumulative energies of the *AE* signals from the joints under torques of 7 N·m and 9 N·m are similar during the fatigue process. Such similarity also occurs in the curves for the joints under torques of 3 and 5 N·m during the first fatigue hour. In **Figure 17(b)**, the degree of bolt loosening, evaluated by the decrease in the compressive strain, is found to decrease with an increase in the applied torque when it is not larger than 7 N·m. From the comparison between **Figures 17(a)** and **(b)**, the released energy of the *AE* signals, to some extent, is found to be capable of qualitatively detecting the state of a bolted joint under vibration fatigue, but not capable of identifying the influence of applied torque on the fatigue process of bolted joints under vibration.

HHT-processed *AE* signal characteristics will be applied to quantitively detect tightening condition of bolted joints subject to vibration fatigue in what follows. As representative results, *HHT* spectra of the *AE* signals (average of 300 signals) from the joints under 3 N·m and 7 N·m over fatigue are comparatively shown in **Figures 18 (a)- (d)**. To observe that *C*-*C* contact-related (*i.e.*, high-frequency) *IMF*s become stronger and distribute in a wider time range after fatigue. Energy ratios of first three *IMF* components of the *AE* signals generated from the bolted joints under different torques over fatigue are exhibited in **Table 1**. For the joints under 3, 5 and 7 N·m, the energy ratios of residual *IMF*s decrease with some fluctuations over fatigue time, which indicates the high-frequency *IMF*s become more intensive after fatigue and is consistent with results as shown in **Figure 18**. While for the joint under 9 N·m, the energy ratio of residual *IMF*s firstly decreases in the first hour and after then it increases. Upon further comparison between variation of compressive strain of the bolts and changes in the energy ratios of residual *IMF*s for the four joints, as shown in **Figure 19**, a considerable consistency in between can be concluded. As representative results, tightening torque of the joint under 9 N·m decreases in the first 1.5 h and increases after then. Similar change trend also presents in the energy ratio of residual *IMF*s. Therefore, the *HHT*-based characteristics of *AE* signals outperform the amplitude (energy)-based *AE* method in the continuous evaluation of tightening condition of the bolted composite joints under vibration fatigue.

5. Conclusions

Evaluation of tightening conditions of bolted composite joints subject to vibration is attempted by directly analyzing the asperity contacts at the *C-C* interface using the *HHT*-based characteristics of *AE* signals in this study. The following conclusions can be drawn according to the experimental findings.

(1) *HHT* shows a higher time-frequency resolution when processing bolt loosening-induced *AE* signals, which possess non-stationary characteristics, compared to *STFT*;

(2) *AE* signals induced by asperity contacts at different contact interfaces (*i.e., C-C* and *M-C* contacts) in bolted composite joints can be discriminated by comparing the time-presentation envelopes and the time-frequency distribution of the *IMF*s in the *HHT* spectrum. In the investigated frequency range, *M-C* contact-related *AE* signals dominate the frequency range between 10 and 40 kHz, while *C-C* contact-related *AE* signals mainly distribute between 20 and 200 kHz;

(3) The gross energy of *AE* signals shows a considerable sensitivity to changes in the residual torque of a bolted composite joint in a limited range. Such method fails to quantitatively detect the tightening condition of joints under vibration fatigue. With usage of *HHT*-based signal characteristics, energy ratios of high-frequency *IMF*s induced by the *C-C* contact achieve an enhanced sensitivity to the decrease in bolt torque. Bolt loosening results in increases in the energy-ratios of the *C-C* contact-related *IMF*s. Based on this, vibration loosening of bolted composite joints under different torques is quantitatively correlated to the increase of energy ratios of *C-C* contact related *IMF*s. On this basis, continuous evaluation of bolted composite joints under vibration fatigue is achieved by the *HHT*-processed characteristics of *AE* signals.

In spite of the promising results reported in this study, there are some problematic issues and challenges remaining for future exploration. Considering intensive attenuation, dispersion properties and signal complexity of the high-frequency acoustic emission propagating in composites, in the current primary study, *AE* signals in a frequency band of 10 -200 kHz were considered. To achieve comprehensive understanding of generation mechanisms of *AE* signals in the bolted composite joint and their quantitative dependence on the tightening torque, frequency analysis in a wider spectrum will be implemented in future study. To extend this method for bolt loosening monitoring in multi-type joints with distinct surface properties, it is necessary to understand the relation between the surface properties (*i.e.,* roughness and material types) and the centered-frequencies of decomposed *IMF*s. To achieve this goal, future work is dedicated to building a theoretical contact model to describe asperity contacts in the mating parts of a bolted joint to facilitate the related numerical investigation.

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