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Continuous Monitoring of Tightening Condition of Bolted Composite Joints Using Intrinsic Mode Functions of Acoustic Emission Signals

Z. Zhang [1, 2]*, Y. Xiao [1], Z. Q. Su [2]

[1] School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai, P.R. China
Email: 2013_tjzhangzhen@tongji.edu.cn ; y_xiao@tongji.edu.cn

[2] Department of Mechanical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong
Email: zhongqing.su@polyu.edu.hk

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ABSTRACT

Intrinsic mode functions (IMFs) 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 IMFs, 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 IMFs were linked to the contact behaviours 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 IMFs. 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 IMFs, 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.

1. Introduction

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 [1-2]. However, during the service lives of bolted composite structures, various factors [3], 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 [4]. Most failures of bolted joints were reported to be caused by metallurgical fatigue, under-tightening, over-tightening and irregular tightening of the bolts.

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

* Corresponding author.

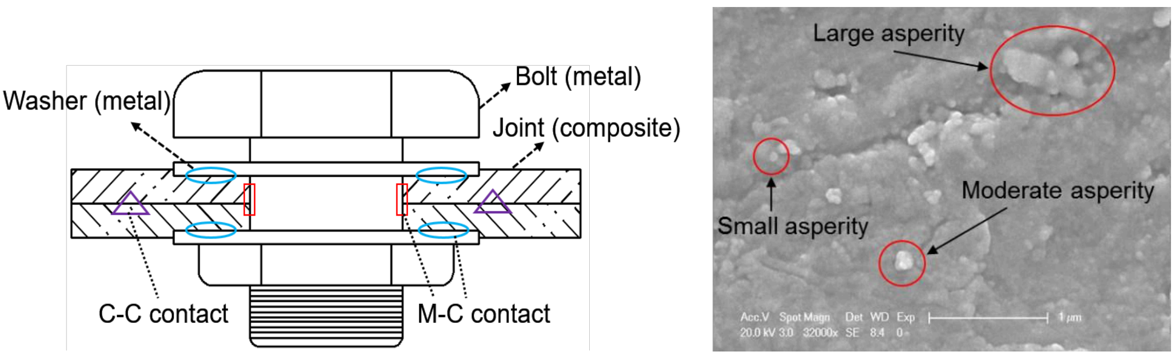
relative motion. The asperities on the two contact surfaces, applied with different degrees of pressure, exhibit certain type of contact behaviour, for example asperity collision, elastic and plastic deformation, or fretting wear (i.e., formation and rupture of adhesion junctions). It was reported that specific contact behaviour at the contact interface can be identified using pattern recognition and frequency analysis of AE signals [5], which have demonstrated their efficiency in characterizing failure modes of carbon fiber reinforced plastics (CFRP). 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) [6-7].

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 IMFs. Subsequently, these IMFs were used as basic functions to recognize the C-C contact related IMFs 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 IMFs, 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 IMFs of the AE signals.

2. Results and Discussions

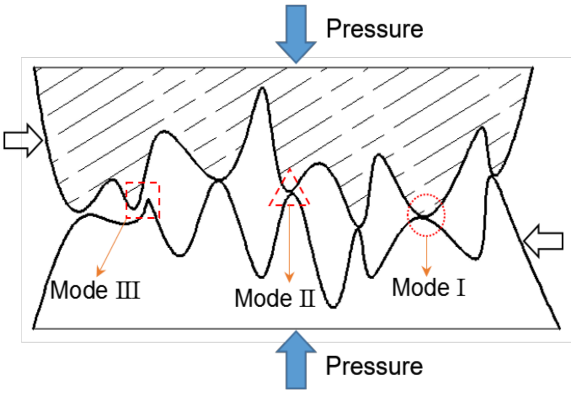
2.1 Hilbert-Huang Transform (HHT) for Bolt Loosening-induced AE Signals

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).

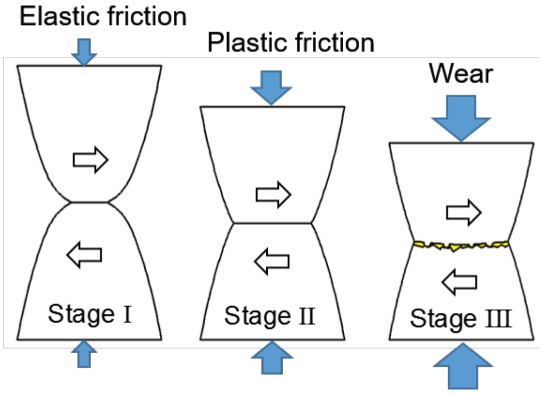


(a) **(b)**

Figure 1. (a) *M-C* and *C-C* contacts in a bolted composite joint; (b) asperities on the composite surface obtained by *SEM*; (c) two contact surfaces at the *C-C* interface undergo a relative motion; and (d) contact behaviors of asperities under increasing pressure



(c)



(d)

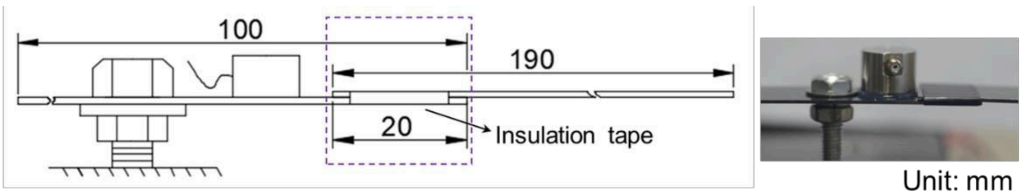
Figure 1 (continue)

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. 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.

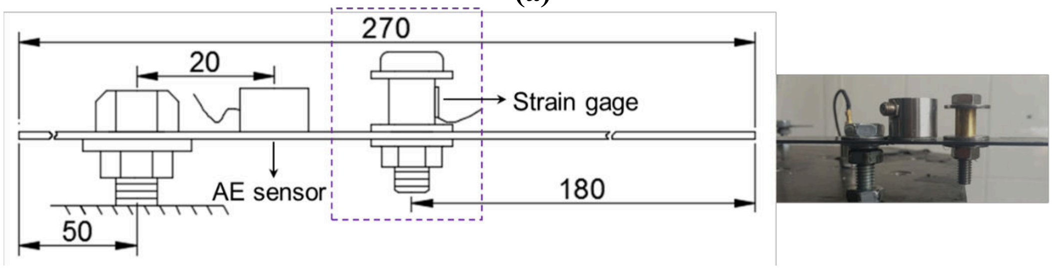
To conclude that the contacts between the three types of asperities naturally generate AE signals with distinct characteristics in terms of time durations and centered frequencies. Upon the occurrence of bolt loosening in a bolted composite joint, a reduce in contact area between asperities, caused by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

2.2 Samples and Experimental Set-up

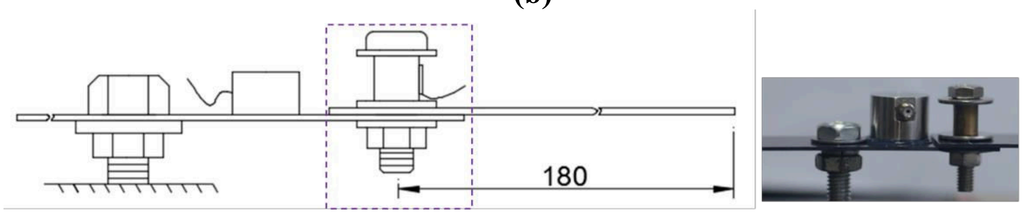
To validate the efficiency of *IMFs* in identifying contact conditions of joint interfaces, three sets of experimental setups were used to capture *AE* signals generated at the single-type contact interface (*i.e., C-C* contact in two assembled composite beams as displayed in Figure 2(a) and *M-C* contact in a bolted beam as shown in Figure 2(b)) and mixed-type contact interface (in a bolted composite joint (see Figure 2(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 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 2(c) but applied with different torques (*i.e.,* 3, 5, 7 and 9 N·m), as displayed in Figure 2(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. 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.



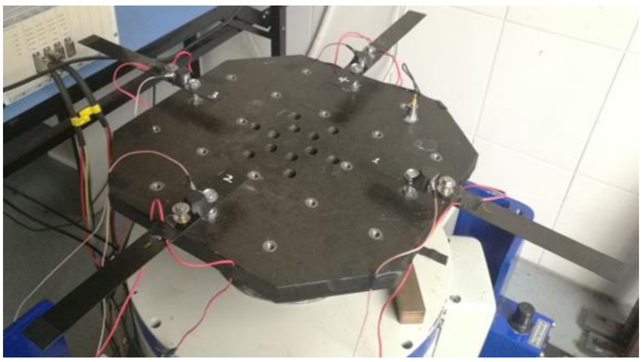
(a)



(b)



(c)

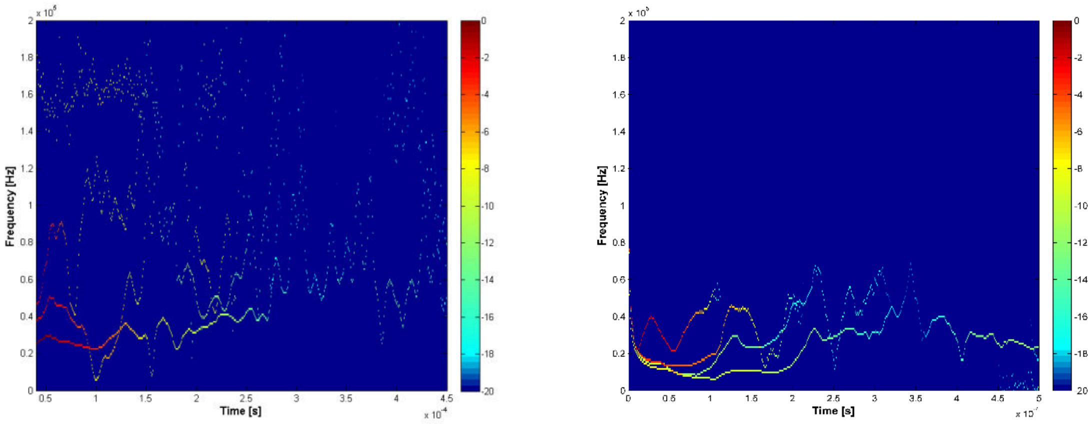


(d)

Figure 2. Experimental set-ups for collecting *AE* signals: (a) in two beams assembled by insulation tape; (b) in a bolted beam; (c) in a bolted joint; and (d) in four bolted joints under fatigue

2.3 Characterization of the Residual Torque of Bolted Composite Joints

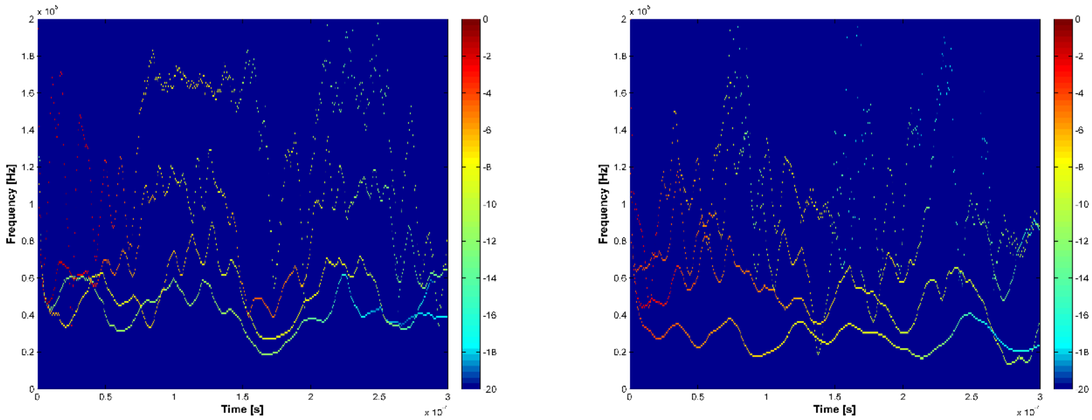
To achieve a quantitative monitoring of bolt torque using the mixed *AE* signals generated from both *C-C* and *M-C* interfaces in a bolted composite joint, unique characteristics and quantitative dependence of these two signals on the applied torque must be firstly understood. Motivated by this, *AE* signals generated at the single-type contact interface (*i.e., C-C* contact as shown in Figure 2(a) and *M-C* contact as shown in Figure 2(b)) are processed with *HHT* and the decomposed *IMF*s are comparably studied to ascertain their distinct characteristics in Figure 3 (a) and (b). 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.



(a) (b)

Figure 3. Hilbert-Huang transform spectra of the *AE* signals from (a) C-C contact and (b) M-C contact

To investigate energy shift in the signals generated from the joint under increasing torque, *HHT* spectra of the signals (first four *IMF*s) from the joints under 1 and 9 N·m are comparably displayed in **Figure 4**. 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.



(a) **(b)**

Figure 4. Hilbert-Huang transform spectra of the *AE* signals from the joint under (a)1 N·m; and (b) 9 N·m

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

$$R_j = E(C_j) / \sum_{j=1}^{n} E(C_j) \times 100\% \tag{1}$$

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 5. 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.

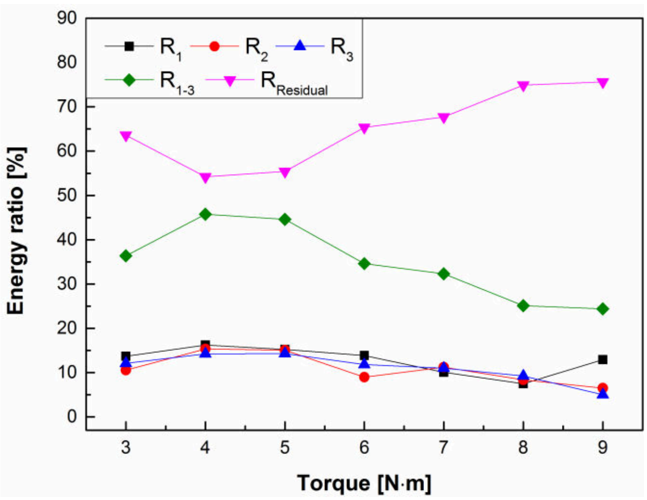


Figure 5. Energy ratios of *IMF* components decomposed from the *AE* signals from joints under different torques

2.4 Monitoring of Vibration Loosening of Bolted Composite Joints

HHT-processed *AE* signal characteristics will be applied to quantitively detect tightening condition of bolted joints subject to vibration fatigue in what follows. Energy ratios of first three *IMF* components of the *AE* signals generated from the bolted joints under different torques over fatigue are exhibited in Figure 6. 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. 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 6, 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.

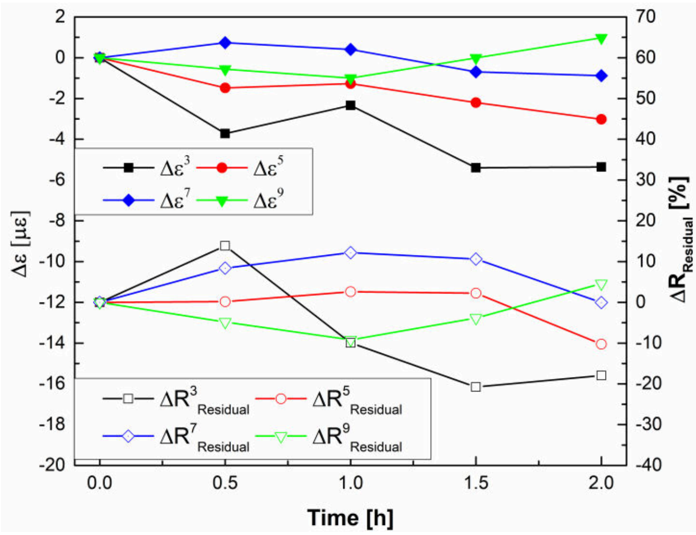


Figure 6. Variation of compressive strain (Δε, unit: με) and energy ratios of residual components ($\Delta R_{Residual}$, unit: %) over fatigue

3. Conclusions

Evaluation of tightening conditions of bolted composite joints subject to vibration is attempted by directly analysing 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) 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 IMFs 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;

(2) 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 IMFs induced by the C-C contact achieve an enhanced sensitivity to the decrease in bolt torque.;

(3) Bolt loosening results in increases in the energy-ratios of the C-C contact-related IMFs. 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 IMFs. On this basis, continuous evaluation of bolted composite joints under vibration fatigue is achieved by the HHT-processed characteristics of AE signals.

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