Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 188 (2017) 278 – 285

Procedia Engineering

www.elsevier.com/locate/procedia

6th Asia Pacific Workshop on Structural Health Monitoring, 6th APWSHM

Continuous Monitoring of Residual Torque of Loose Bolt in A Bolted Joint

Zhen Zhang[a,b], Menglong Liu[a], Zhongqing Su[a,c]*, Yi Xiao[b]

[a]The Hong Kong Polytechnic University, No.11 Yuk Choi Road, Hong Kong, Hong Kong SAR
[b]Tongji University, No.1239 Siping Road, Shanghai 200092, P.R.China
[c]The Hong Kong Polytechnic University Shenzhen Research Institute, No.18 Yuexing Road, Shenzhen 518057, P.R.China

Abstract

Bolted joints are ubiquitous in engineering assets, performing a critical role of transferring loads among interconnecting components. Effectual inspection and monitoring of loosening of the bolts throughout their intended service life warrants a reliable service of the joints. In this study, identification of bolt loosening and quantitative estimate of the residual torque for three types of joints was attempted, theoretically and experimentally, using two approaches in a comparative manner: a wave energy dissipation (WED)-based linear acoustic approach and a contact acoustic nonlinearity (CAN)-based vibro-acoustic modulation (VM) method. In the former, an analytical model, residing on the Hertzian contact theory, was established to link the WED to the residual torque of a loose bolt. In the latter, the contact stiffness at the interconnecting interface, when a pumping vibration introducing perturbation to probing waves, was calibrated in terms of a Tayler series, on which basis a modulation index was constructed. With the index, nonlinear signal spectral features were quantitatively associated with residual torque. The two approaches were validated experimentally, to find a good agreement between theoretical prediction and experimental estimate. The comparison between two approaches reveals that the nonlinear VM-based method offers enhanced accuracy and sensitivity to bolt loosening than a linear WED-based approach, with additional capacity of detecting bolt loosening in multi-type joints.

Peer-review under responsibility of the organizing committee of the 6th APWSHM

Keywords: Bolted joint; bolt loosening; contact acoustic nonlinearity; vibro-acoustic modualtion; wave energy dissipation

* Corresponding author. Tel.: +852-2766-7818; fax: +852-2365-4703.
E-mail address: zhongqing.su@polyu.edu.hk

Peer-review under responsibility of the organizing committee of the 6th APWSHM
doi:10.1016/j.proeng.2017.04.485

1. Introduction

To meet the demand of design and maintenance in engineering practice, multi-type of bolted joints, including cross-lap and single-lap joints, are widely used to assemble primary structural components [1]. For instance, approximately 3 million rivets and other fasteners are used to assemble more than 130,000 unique engineered parts in a Boeing 777 airplane. Throughout the service life of a bolted joint, various diatheses, including cyclic loads, high-temperature and -humidity working conditions, and structural ageing, can initiate and accelerate relaxation of the pre-load of a bolt [1], potentially leading to catastrophic consequences without timely awareness. The vast hazard committed by bolt loosening has posed an urgent need for continuous monitoring of the tension leftover of bolts, to assure an adequate level of integrity and durability of joints, whose importance cannot be overemphasized.

However, current inspection techniques to serve this purpose are still represented by those that are somewhat primary (*e.g.*, visual and tapping inspection) and performed at regularly scheduled intervals. Such an interruption or removal process is time-consuming, labor-intensive, and lack of accuracy. In this backdrop, great efforts have been directed to the development of alternative methodologies, making good use of linear features of acoustic waves (*e.g.*, energy dissipation [1], change in ultrasonic velocity [2], and piezoelectric impedance [3]). Representatively, Yang and Chang [1] constructed a bolt loosening indicator (*i.e.*, specific damping ratio) based on the energy dissipation of Lamb waves when traversing the bolted region in a cross-lap joint. Within a certain range of residual torque, the energy dissipation was found to increase with the increase in the applied torque. Amerini and Meo [4] developed a similar linear index (*i.e.*, acoustic moment) to identify bolt loosening in a single-lap bolted joint. However, a contradicting conclusion that energy dissipation decreases as the applied torque decreasing, was drawn according to the experimental observation. Such an opposite trend of variation in WED can be attributed to the difference in lap configuration between the cross-lap and the single-lap bolted joints. Consequently, this high dependence of WED on joint type arises immense difficulty in evaluating the leftover torque of a bolt if the joint type is unknown beforehand or these two types of joints are mixing used. On top of this, early bolt loosening, analogous to an undersized crack, is not inclined to induce perceivable wave dissipation, which further lowers the effectiveness of liner acoustic wave method.

It is commonly accepted that the sensitivity of nonlinear acoustic methods to damage features (*e.g.*, a crack or a loose bolt) is far greater than that of linear acoustic methods (*e.g.*, measure of wave dissipation) [5]. To fulfill the task of quantitating bolt loosening at an early stage, sharing a similar principle in detecting “breathing” fatigue cracks [6], vibro-acoustic modulation(VM)-based method, which resides on contact acoustic nonlinearity, has been spotlighted. In this approach, a mixed excitation, namely a low-frequency (LF) pumping vibration and a high-frequency (HF) probing wave, are simultaneously applied on the monitored structure, to interact with the “imperfect” contact due to a crack or a loose bolt. The pumping vibration drives the “imperfect” contact interface to close and open periodically (“breathing” motion), and introduces a perturbation to the probing wave and appearance of nonlinear signal features such as additional sidebands in signal spectra. Consequently, the magnitude of a sideband (either left sideband (LS) or right sideband (RS)) can be related to the severity of a crack or bolt loosening [7].

In this study, nonlinear vibro-acoustic modulation (VM)-based method was developed for the early detection of bolt loosening in multi-type bolted aluminum joints. In the framework, a wave energy dissipation (WED)-based linear acoustic method and a vibro-acoustic modulation (VM)-based nonlinear approach were compared in terms of respective efficiency and sensitivity to bolt loosening. In the former, an analytical model, based on the Hertzian contact theory, was proposed to construct a linear index to correlate the residual torque with WED; in the latter, CAN engendered at the joining interface was explored to develop a nonlinear index, associating signal spectral features (e.g., sidebands) with the residual torque. Both approaches were validated experimentally, in a comparative manner, by evaluating the residual torques of a loose bolt in single-lap, cross-lap and hybrid-lap joints, respectively.

2. Theory: From linear to nonlinear

2.1. Linear index: WED-based

A formula for calculating the preload P when a bolt is tightened with a torque T is widely expressed as

$$P = \frac{T}{\tau d} \tag{1}$$

where τ is a thread coefficient subject to the friction between the nut and bolt, and d the bolt diameter.

Upon interacting with a bolt, some part of the incident Lamb wave continues its propagation in Assembly I after transmitting the bolt, named as transmitted wave carrying energy $\Omega_{transmitted\ in\ I}$; and some other leaks to Assembly II via the bolt, named as leak wave carrying energy Ω_{leak}, and then propagates in Assembly II, as shown in Fig. 1.

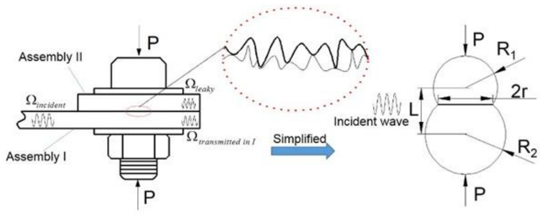

Fig. 1. A simplified model for a bolted joint for WED-based linear method.

The amount of leak wave is assumed proportional to the substantial contact area (determined by the contact force) of the two contact surfaces, which are rough in the micro respect [1, 7]. Consequently, the relation between the leak energy and applied torque T can be written as

$$\Omega_{leak} \propto S \propto P^{2/3} \propto T^{2/3} \tag{2}$$

From Eq. (2), it is axiomatic that Ω_{leak} inclines to increase as T increases, and in the meanwhile $\Omega_{transmitted\ in\ I}$ decreases provided the incident energy remains unchanged. Based on this, Ω_{leak} and $\Omega_{transmitted\ in\ I}$ can serve as a damage index (denoted by linear index η in what follows) to quantitatively indicate the degree of bolt loosening in the single-lap and cross-lap bolted joint, respectively.

2.2. Nonlinear index: VM-based

Extending the above modeling from linear to a nonlinear regime, now consider that the joint is subject to a mixed excitation, namely the pumping vibration and probing wave. A single-degree-of-freedom system, shown schematically in Fig. 2 was used to describe the dynamic response of a joint subjected to LF pumping vibration (with an equivalent force $F_1 cos\omega_1 t$) and HF probing wave (with an equivalent force $F_2 cos\omega_2 t$), the equation of motion of the joint can be described as

$$M\ddot{x} + K_1 x - \varepsilon K_2 x^2 = F_1 \cos\omega_1 t + F_2 \cos\omega_2 t \tag{3}$$

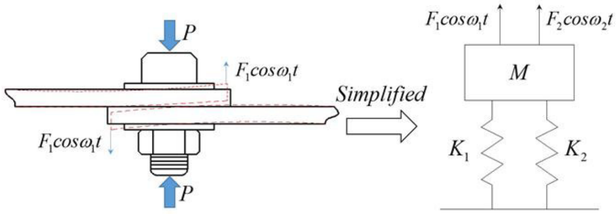

Fig. 2. A simplified model for a bolted joint for VM-based nonlinear method.

where M denotes the mass and t the time. The term with K_2 represents a second-order perturbation in which ε is a small quantity to scale the perturbation to be minute. Here, simple power-law pressure-dependent contact stiffnesses of the bolted interface, including the linear contact stiffness K_1, which decreases as T increasing, and nonlinear contact stiffness K_2, which increases with an increase in T.

Using the perturbation theory, the solution to Eq. (3) takes the following form

$$x = x_1 + x_2 \quad (4)$$

x_1 and x_2 represents the linear and nonlinear dynamic responses of the joint to the mixed excitation, respectively. Further, upon neglecting the transient components, x_1 can be obtained as

$$x_1 = \frac{F_1}{K_1 - M\omega_1^2} cos\omega_1 t + \frac{F_2}{K_2 - M\omega_2^2} cos\omega_2 t \quad (5)$$

The responses of sidebands $x_{sidebands}$ including in the nonlinear responses x_2 can be expressed as

$$x_{sidebands} = \frac{G_1 G_2}{K_1 - M(\omega_1 + \omega_2)^2} K_2 \cos(\omega_1 + \omega_2)t + \frac{G_1 G_2}{K_1 - M(\omega_1 - \omega_2)^2} K_2 \cos(\omega_1 - \omega_2)t \quad (6)$$

From Eq. (6), it can be noted that the magnitude of a sideband is proportional linearly to the nonlinear contact stiffness K_2, which increases with a decrease in the residual torque T of the bolt. Consequently, based on Eq. (6), a damage index, β, embracing the magnitudes of the left (A_L, in the unit of dB), right (A_R) sidebands and the probing wave (A_{HF}) in spectral is defined, given that the change of linear response subjected to the variation of pumping vibration can be neglected, as

$$\beta = \frac{(A_L + A_R)}{2} - A_{HF} \quad (7)$$

β is called nonlinear index, in parallel with the linear index η defined earlier. From above analysis, it can be predicted that β decreases with an augment in the residual torque T. In addition, it is noteworthy that the above derivation is not restricted by the type of a joint, and therefore β is applicable to any joint type.

3. Experimental validation

3.1. Linear index: WED-based

The proposed inspection framework was validated experimentally. Three types of bolted joints, including a single-lap (Type I), a cross-lap (Type II) and a hybrid (comprising both single- and cross- laps) (Type III) bolted aluminum alloy joints, were considered, as shown in Figs. 3(a), (b) and (c), respectively. In particular, the hybrid joint (Type III) was aimed at testifying the performance of the two indices towards multi-type joints. Dimensions of each joint are indicated in Figs. 3. The right end of each joint was fixed to form a cantilever. M6 bolts were used in all the three connections. Two PZT wafers were surface-mounted on each joint, 112.5 mm from the bolt, one serving as the actuator (PZT1) and the other as the sensor (PZT2). A 14-cycle Hanning window-modulated sinusoidal tone-burst signal at a central frequency of 310 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 Lamb waves into the joint. The wave propagation, upon traversing the bolt, was monitored by PZT_2 using an oscilloscope (Agilent® DSO9064A) at a sampling frequency of 20 MHz. Captured Lamb wave signals were averaged 64 times to remove random measurement noise.

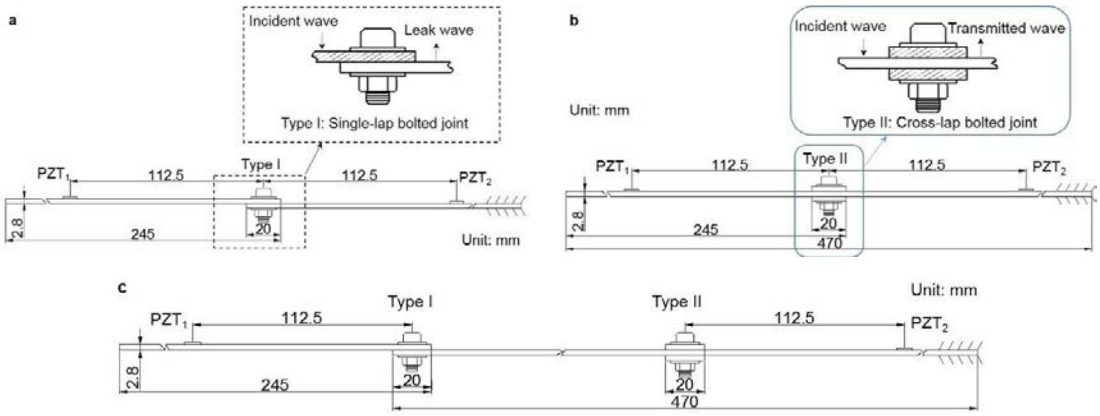

Fig. 3. Specimen configurations (for WED-based linear method): (a) single-lap (Type I); (b) cross-lap (Type II); and (c) hybrid-lap (Type III)

Fast Fourier Transform (FFT) was performed on captured signals, to ascertain distribution of wave energy in the frequency domain (see Fig. 4). The majority of the wave energy is observed to be in a range from 270 to 350 kHz. Subsequently, the linear index η (*e.g.*, $\Omega_{transmitted\ in\ I}$ and Ω_{leak}) was integrated within this frequency range.

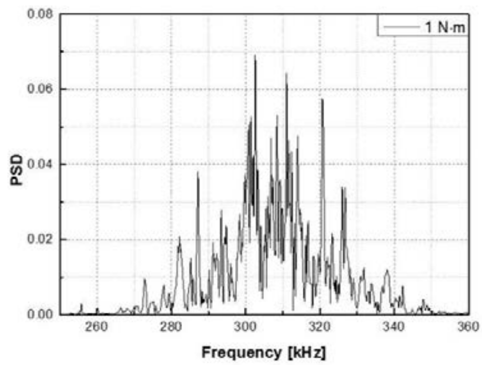

Fig. 4. Spectrum of acquired Lamb wave signal upon traversing the matting part of the single-lap bolted joint under 1 N·m

3.2. Nonlinear index: VM-based

The same specimens with unchanged boundary conditions were recalled, in Fig. 5, to validate the VM-based approach and the nonlinear index β. A piezo stack actuator (PI®, P-885.11) was surface-mounted on each joint to generate HF probing waves, while a shaker (B&K®, Model type: 4809) was used to introduce a point-force-like LF pumping vibration to the joint. Two sinusoidal signals at different frequencies were generated by a waveform generator (HIOKI®, Model Type: 7075), to supply the stack actuator and the shaker, respectively. A power amplifier (B&K®, Model Type: 2706) intensified the pumping vibration. The response signal of the joint under the mixed excitation was captured with an accelerometer (B&K®, Model Type: 4393) and registered using an oscilloscope (Agilent® DSO9064A) at a sampling frequency of 200 kHz.

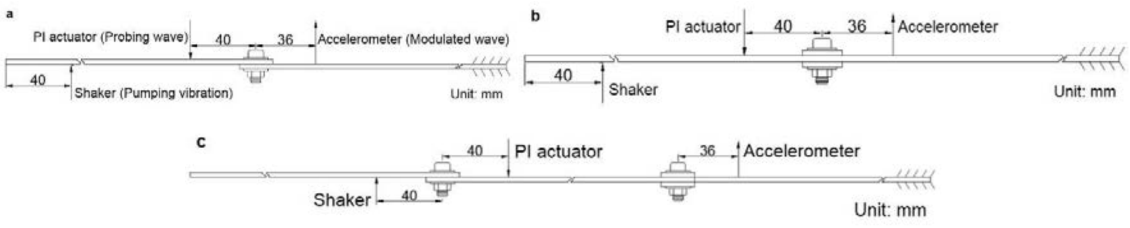

Fig. 5. Specimen configurations (for VM-based nonlinear method): (a) single-lap (Type I); (b) cross-lap (Type II); and (c) hybrid-lap (Type III)

To maximize the vibro-acoustic effect of a loose joint under the mixed excitation, excitation frequencies of the pumping vibration and probing wave were selected prudentially. The excitation frequency of pumping vibration was selected from the low-order natural frequencies, which produces the second-order harmonic with the strongest magnitude, indicating a high degree of nonlinearity in structural responses. Following this principle, 992 Hz was selected as the frequency for pumping vibration for Type I joint. In an analogous manner, 1145 Hz and 1303 Hz were selected for Type II and Type III joints as the frequency of LF pumping vibration, respectively.

To determine the frequency of the HF probing wave, three types of joints were excited using a white noise via the PI actuator, respectively, to obtain their respective spectra, from which the strongest response to the excitation frequency of each joint, was ascertained. Subsequently, 14.240 kHz ,14.777 kHz and 15.049 kHz were selected for Type I, Type II and Type III joints as the frequency of HF probing wave, respectively.

As representative results, time-frequency spectra of Type I joint, subjected to the mixed excitation, under two extreme situations: 1 N·m (full loosening) and 13 N·m (full tightening) are displayed in Fig. 6(a) and (b), respectively.

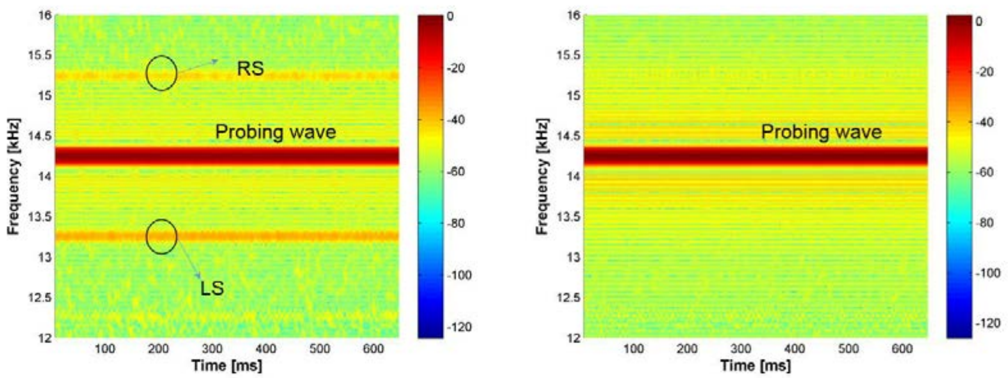

Fig. 6. Time-frequency spectra of response of single-lap joints when *T* is (a) 1 N·m (full loosening); and (b) 13 N·m (full tightening)

An occurrence of a strong sideband is found when the bolt is fully loose (Fig. 6 (a)), while a fairly weak sideband when the bolt is fully fastened (Fig. 6(b)). Conclusion can therefore be drawn that the magnitude of sideband can serve as an indicator to calibrate the degree of bolt loosening.

4. Results

To compare the detectability between WED-based linear and VM-based nonlinear method for the three types of joints in a quantitative manner, linear index η and nonlinear index β, subject to residual torque T, are calculated and displayed in Fig. 7, for three types of joints. From the comparison, it is apparent that the nonlinear method outperforms the linear method holistically, evidenced by the following observations:

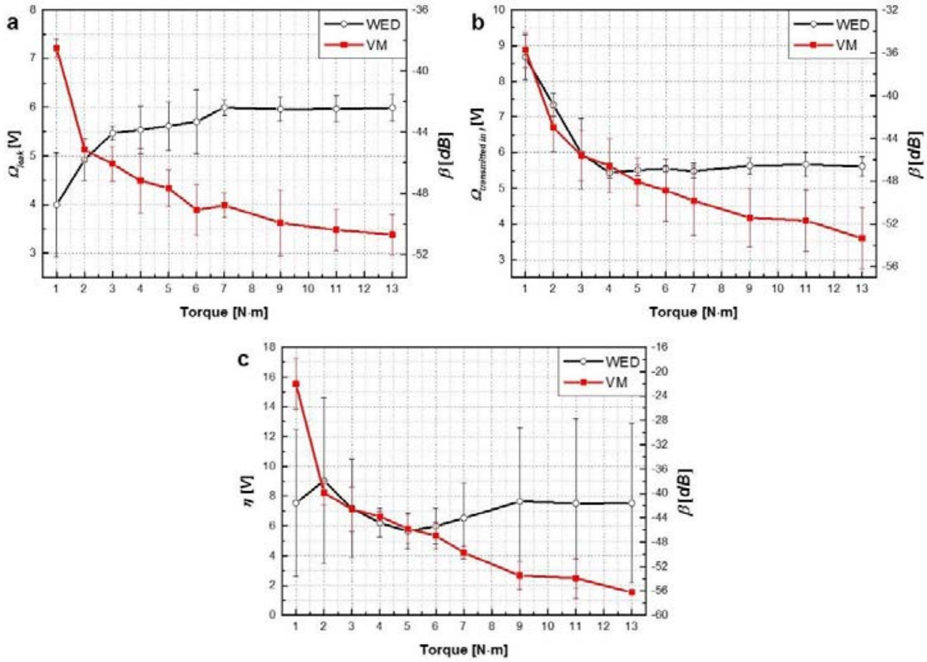

Fig. 7. Linear and nonlinear indices vs. residual torque *T* for (a) single-lap (Type I); (b) cross-lap (Type II); and (c) hybrid-lap (Type III)

- Both linear and nonlinear indices present monotonic tendency, subject to the residual torque, for both single-lap (see Fig. 7(a)) and cross-lap (see Fig. 7(b)) joints. However, for the hybrid-lap joint, as displayed in Fig. 7(c), the linear method may fail to predict the residual torque; on the contrary, the nonlinear approach is capable of evaluating the torque, regardless of the joint type;
- Observing Figs. 7(a) and (b), the linear index is observed to show the best sensitivity to bolt loosening in a limited range. For example, for Type I joint, this range is from 7 N·m down to 1 N·m, and from 4 N·m down to 1 N·m for Type II joint; on the other hand, the sensitivity of the nonlinear index persists throughout the whole range from fully fastened to fully loose, showing enhanced sensitivity than its linear counterpart; and
- particularly, when the bolt loosening is at an early stage (when *T* is not less than 11 N·m in this study), the nonlinear index exhibits much higher sensitivity over the linear index. This highlights good detectability of the nonlinear approach in evaluating early bolt loosening

5. Conclusion

A hybrid method, namely a wave energy dissipation (WED)-based linear acoustic approach and a vibro-acoustic modulation (VM)-based nonlinear method, was comparably adopted to identify bolt loosening for three types of joints, both theoretically and experimentally. The linear index, defined in terms of leaked or transmitted energy of incident waves upon traversing a loose bolt, is found to increase as the applied torque increases in a single-lap bolted joint, but decreases in a cross-lap bolted joint, showing high dependence on the joint type. In addition, bolt loosening at the early stage would not introduce a phenomenal change in the substantial contact area, as a result the detectability is limited when using the linear method. In the nonlinear approach, sidebands in signal spectra induced due to contact acoustic nonlinearity (CAN), when the joint is subjected to the mixed excitation, are found quantitatively related to the degree of bolt loosening. For both methods, the theoretical prediction and experimental validation are in a good agreement. The nonlinear VM-based method shows enhanced sensitivity to bolt loosening than a linear WED-based approach, with additional merit to detect multi-type joints and early stage of bolt loosening. In addition, with a capability of built-in sensing using miniaturized sensors (PZT in this study), the approach can be implemented in a real-time, automatic, and prompt manner, thus rendering a potential to be extended to online health monitoring (SHM) for bolted structures.

Acknowledgements

This project is supported by the Hong Kong Research Grants Council via General Research Funds (No. 523313 and No. 15214414). This project is also supported by National Natural Science Foundation of China (Grant No. 51375414).

References

[1] J. Yang, F.K. Chang, Detection of bolt loosening in C–C composite thermal protection panels: I. Diagnostic principle. Smart Mater. Struct 15 (2006) 581-590.

[2] K.Y. Jhang, H.H. Quan, J. Ha, N.Y. Kim, Estimation of clamping force in high-tension bolts through ultrasonic velocity measurement. Ultrasonics 44 (2006) 1339-1342.

[3] Y.K. An, H. Sohn, Integrated impedance and guided wave based damage detection. Mech. Syst. Signal Pr. 28 (2012) 50-62.

[4] F. Amerini, M. Meo, Structural health monitoring of bolted joints using linear and nonlinear acoustic/ultrasound methods. Struct. Health Monit. 10 (2011) 659-672.

[5] K.A. Van Den Abeele, P.A. Johnson, A. Sutin, Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, part I: nonlinear wave modulation spectroscopy (NWMS). Res. Nondestruct Eval. 12 (2000) 17-30.

[6] M. Hong, Z. Su, Q. Wang, L. Cheng, X. Qing, Modeling nonlinearities of ultrasonic waves for fatigue damage characterization: theory, simulation, and experimental validation. Ultrasonics 54 (2014) 770-778.

[7] Z. Zhang, M. Liu, Z. Su, Y. Xiao, Evaluation of bolt loosening using a hybrid approach based on contact acoustic nonlinearity. in: 19th World Conference on Non-Destructive Testing, Munich, 2016.