AN IMPROVED DIAGNOSTIC METHOD FOR DETECTION OF BOLT LOOSENING IN THERMAL PROTECTION PANELS

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Abstract

Research and development efforts are underway to provide structural health monitoring systems to ensure the integrity of thermal protection system (TPS). In this paper, a smart washer was integrated into the TPS with an embedded piezoelectric element used as an actuator to generate the propagating waves as well as a sensor to receive the diagnostic waves. Theoretical and experimental analyses were completed to demonstrate the feasibility of detecting loose fasteners in a TPS. Based on the damping phenomena of ultrasonic waves across the bolted joints, an improved analytical method was proposed to assess the fastener integrity of a bolted structure; the computing process was simplified greatly by using energy and attenuation time as the extracted features. Experimental results show that this method is capable of locating the loosened bolts, as well as quantifying the degree of panel and bracket bolt loosening.

1 Introduction

Space vehicles experience harsh environments during the mission, which include high temperature gradients, aerodynamic acoustics, and impacts. Undetected damage or failure in the TPS can lead to catastrophes such as the Columbia disaster, and the accident happened to the space shuttle Discovery which has been launched recently. Two pieces dropped from the fuel tank. Fortunately they did not crash into the shuttle; otherwise the consequence would be inconceivable. Here are two other requirements for developing a new structural health monitoring system besides the security, that is, to reduce the cost and to shorten the downtime of space vehicles after a mission. NASA started some years ago a second generation RLV program aiming at reducing launch cost of an order of magnitude and improving the security by 100 times over current conditions. Goals for the third generation RLV program are 100 times cheaper and 10000 times safer [1]. Currently, the maintenance procedure of TPS is extremely time consuming and expensive due to its heavy reliance on human labor. According to the statistics [2], currently 27% of an average aircraft's life cycle cost, both for commercial and military vehicles, is spent on inspection and repair. Maintenance is the largest obstacle in shortening the downtime of space vehicles. Therefore a new health monitoring system for the thermal protection systems must be developed to reduce the downtime as well as to increase the safety margin and to reduce maintenance costs.

Up to now, there are many types of the thermal protection systems, including ceramic tiles, carbon–carbon panels, stand-off heat shields, multiwall concepts, prepackaged superalloy honeycomb sandwich panels and so on; they are attached to the body of RLV by fasteners or adhesive. Carbon–carbon panels mounted with bracket joints are potential future thermal protection systems with such features as light weight, low creep, and high stiffness at high temperature [3]. It is the most critical to keep the integrity of the TPS panels for a RLV during a mission. Due to the heat, aerodynamic/acoustic noise, and debris impact, the TPS panels are exposed to many possible failures, for example, facesheet breach, burnthrough, over-temperature of the structure, coating removal, and so on. However, one of the most probable, and also the most dangerous failure mode is the mechanical detachment of the TPS panels from the base structure which can lead to hot air's penetration into the detachment gap during the re-entry heating process. This can cause subsystem's malfunction and in the worst case, the loss of vehicle and crews through a chain reaction.

2 Current Research Statuses and Development of TPS Health Monitoring

There are two key problems restricting the development of the panel-type TPS structure health monitoring: one is its special application environment, and the other is its complicated structural configuration. Its special flight environment make the structural health monitoring very difficult. To summarize, the primary problems are:

- How to choose the appropriate sensors that can inspect any failure mode.
- How to integrate the sensors to the structure without modification of the existing structure.
- How to design the sensors to minimize their impact on the structural performance, the increase of the mass and the cost.
- How to distribute the sensors sites to ensure their sensitivity and safety.
- How to develop a arithmetic method that can be used to detect damage quickly, locate the position, and even predict the residual life.

Viewed from the complicated structural configuration, the panel-type TPS include two typical structural styles. The difference lies in the panel. One is reinforced carbon-carbon (RCC) or Advanced Carbon-Carbon (ACC) [4] panel, and the latter material has better mechanical properties than the former, in terms of improved strength, temperature capacity and oxidation resistance. This type of panel is located along the wing leading edges and nosecone that are the hottest position. The other category of panel is metallic honeycomb sandwich panels, which is used to cover the large surface area of RLV, but the complicated configuration makes its inspection more difficult. However, whatever the panel type is, its primary damage and failure modes are generally the same. Defects on the TPS were categorized into four levels in reference [5]: 1. Loosening of base brackets; 2. Loosening of panels; 3. Impact events; and 4. Severe panel damages. These four damage modes are the main parts to be monitored as illustrated in figure 1 [5].

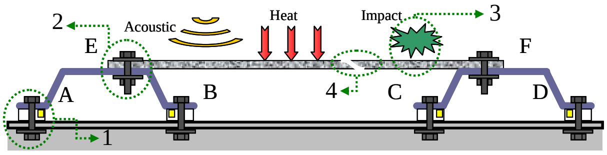


Fig. 1. Damage modes to be monitored on the TPS panels

Although the structural health monitoring (SHM) has been widely studied, applications on the high temperature structures such as TPS are far from enough. TPS is one of the most important key technologies to realize the RLV program, and the real-time monitoring in it is very difficult to realize. The researches on the TPS health monitoring in the world are carried out primarily by the following institutions: Stanford University, NASA Ames Research Center, Korteks Advanced Sciences Corporation and ESA (European Space Agency). They have cooperated with each other and carried out many exploring and initiative studies.

A hierarchical health monitoring system is proposed by Fu-Kuo Chang and Jinkyu Yang [3-5], which can locate the fasteners' loosing positions and estimate the level of the loosing with a built-in PZT sensor with the energy and specific damping capacity (SDC) used as the feature to interpret signals measured from the sensors. A qualitative analysis was given by Mark Derriso [6-7] and Steven Olson [7]. Four PZT transducers are attached to the metallic backing structure to get the structural dynamics and model shape of C-C panel; frequency intervals are used to provide features for the structural health monitoring classifier. Frank S. Milos [8-9] developed a device named "SensorTags", which can be embedded in the thermal protection system to monitor temperature or other parameters of interest. David G. Watters [8, 10] developed an active "wireless" sensors integrated with radio-frequency identification circuits to enable non-contact communication of temperature data through aerospace thermal protection materials. ESA [1] verified the possibility of embedding fiber optic sensors into metallic materials subjected to particularly critical thermal treatments. A SMART Layer™ manufactured by Acellent Technologies, Inc was proposed to monitor crack growth at rivet holes and de-bond between the skins and the honeycomb core of a sandwich structure by Jeong-Beom Ihn [11] and Fu-Kuo Chang [11-12] respectively.

An improved method based on what Jinkyu Yang [13-15] proposed was given in this study, and the energy and attenuation time were used as the extracted features so that the calculation efficiency was increased greatly. Experimental analysis was completed using composite laminate and aluminum plate as the panel; results show that this method can be used easily to identify the panel and bracket bolt loosening. These form a sound basis for studying other modes of damages.

3 Diagnostic Methodology

Damage detection as the basis for structural health monitoring is always an active research field. There are many kinds of detection methods, which can be classified into two categories technologically: one is modal-based method, and the other is experimental data processing based method. The modal-based approach is to excite the entire structure to search for changes in structural dynamic features that reflect damage, and this method has been primarily utilized for the detection of fastener loosening in bolted structures. Mark Derriso et al [6] investigated the fastener torque values using the low-frequency mode shapes of the healthy and damaged bolted C–C TPS structure. Such global approaches are not efficient in recognizing a specific location of the loosened bolted joint in a large structure with numerous joints. Peairs [16] introduced such an impedance based method to detect bolt-loosening phenomena. However, the method is not applicable to the extremely heated RLV TPS panels. The complicated configuration of the mechanical fasteners and the harsh space environments in terms of temperatures and mechanical loads impose numerous constraints on the design and application of a sensory system.

The experimental data processing based method needn’t recognize the dynamic parameters of the configuration. The damage detection is completed by comparing the damaged structure with the response signals or some extracted features of response signals of the undamaged structure. In the wave-propagation-based techniques, it is possible to excite a structure to produce various types of elastic waves, such as Rayleigh waves in thick structures, shear and extensional waves, and Lamb waves in plate or shell structures, by supplying short-term diagnostic waves. The basic concept of this method is sending diagnostic waves from an actuator and receiving response signals that characterize the defects at the other sensor. Energy dissipation propagating waves are unavoidable in structure, and it’ll get more serious around the fasteners and defects area. These changes will all be contained in the measured response signals, so the energy is usually used as an extracted feature of experimental data.

For the panel-type TPS, the panel is mechanically fastened to brackets, which are then bolted to the base structure. The TPS health monitoring system is required to be able to identify the bolt loosening by the response signals received. The connection condition will change with the loose of the bolts, while the change of connection condition will affect the transmitted energy, so the extracted feature of energy can be used to identify the bolt loosing. In reference [14], contact mechanics was utilized to analyze the effects of interface integrity at a bolted joint on the energy transmission. For the bolted joints of panel and brackets, whichever ones were fastened will enlarge the contact area and lose more energy in forms of leakage and dissipation. It is proved that the received energy E_r is in inverse proportion to the square root of the torque applied to the bolts of panel or brackets:

$$E_r \propto 1 - c\sqrt{T_{p,b}} \qquad (1)$$

Where T_p and T_b are the torque of the panel and bracket joints respectively. For an actual sensor signal, the energy of the sensor signal can be expressed as sum of the squares of amplitude of the sensor signal in the discrete time domain $[t_s, t_f]$ as follows [13]:

$$E_r = \frac{2\pi}{w_s} \sum_{t=t_s}^{t=t_f} V[t]^2 \qquad (2)$$

Where $V[t]$ and w_s denote respectively the discrete sensor signal and its sampling frequency, and t_s and t_f are starting time and finish time respectively. In fact, the unit of the 'energy' in equation (2) is $[V^2 \cdot s]$, which is not the unit for physical energy. However, the continuous form of equation (2) is equivalent in mathematical expression to the electrical energy stored in the PZT ceramic. The higher amplitude of sensor signals implies larger energy in general, while lower energy means less sensor voltage.

An important improvement of the diagnostic method based on the works of pioneers was proposed, in which the attenuation time was used as the second feature to monitor the loosening of the bolts instead of specific damping capacity (SDC). Internal damping is an inherence attribute of the materials, which are not equal of different materials. From a qualitative perspective of the wave attenuation, a material with low intrinsic damping produces a slower decay, whereas a high-damping material causes a faster attenuation of the propagating waves. The overall internal damping will increase when the structure is integrated with a higher damping material, and decrease when integrated with a lower damping material. Specific damping capacity (SDC) was used as the second feature to describe the attenuation speed of the sensor signal in references [4, 13-15], but there are two shortcomings to do so.

First of all, this method is under the assumption that the attenuated signal takes a perfect exponential form, but this assumption is only applicable to ideal linear damping. In reality, the amplitude of propagating waves in a dissipative medium does not follow the exponential shape identically, but rather reveals an irregular pattern. It is because that the medium is not the ideal linear damping materials, and the overall damping is not only related to the internal damping of the material but also related to the structural configuration, and energy dissipation phenomena is more serious in the imperfect interface, such as the bolted joints and mechanical fasteners. It was found that the measured sensor signals of experiments are not a smoothly exponential curve. Results show that sensor signals contain high frequency elements with irregular peaks as revealed in figure 2, and some signals even contain obvious irregular dentate envelope amplitude. It is difficult for these signals to take similar form of exponentially decaying curves even after using the running mean technique. So in fact, there must be some errors between the actual decaying curves and the further fitting curves using the least mean square technique.

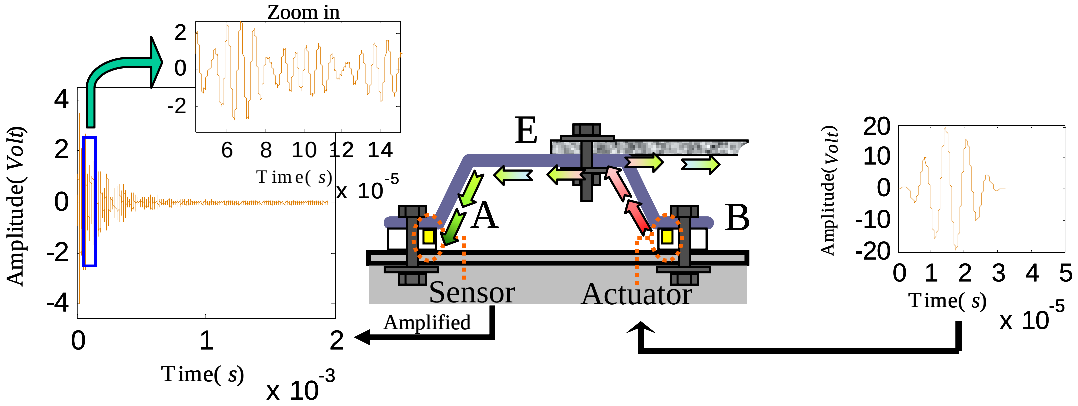


Fig. 2. The propagation of diagnostic wave in the panel-type TPS

Secondly, a complicated and huge computing is needed to get the second feature, because the received signals contain quite complicated information, and they are not the ideal exponential decaying curves. First a running mean technique was used by Jinkyu Yang [4] to get the envelope of the sensor signal. Then a least mean square technique was used to make the fitting curves taking the form of exponential curve. Although the decaying curve produced after these processes can approximately describe the response signals to some extent, the solution process contains large amounts of multiplication and addition operations, and it is hard to avoid the errors.

The attenuation time (AT) is used as the second feature in this study, which is defined as the time consumed for the response signal to attenuate to a certain percent of its maximum amplitude. 0.15 is used as the threshold value in this study, which means the received signal amplitude will attenuate to 15 percent of its maximum amplitude after T_{AT} seconds, where T_{AT} denotes the attenuation time, and it can be represented in a mathematical formula as the following:

$$\left|V_{T_{AT}}\right| / \left|V_{MAX}\right| = 0.15 \qquad (3)$$

Here V_{MAX} is the maximum amplitude of the received signals.

There are two benefits to use attenuation time as the feature. First of all, this method is applicable to any response signals and can be used to analyze any type of attenuation signals, especially those response signals whose attenuation patterns are quite different from those ideal exponential decaying curves. The attenuation time can be used to describe the attenuation speed of the sensor signals whatever types the decaying curve is. For the normalized attenuation curves, as shown in figure 3, the following relationship can be deduced:

$$T_{AT1} < T_{AT2} < T_{AT3} \qquad (4)$$

Where T_{AT1}, T_{AT1} and T_{AT1} are the attenuation time of decaying curves.

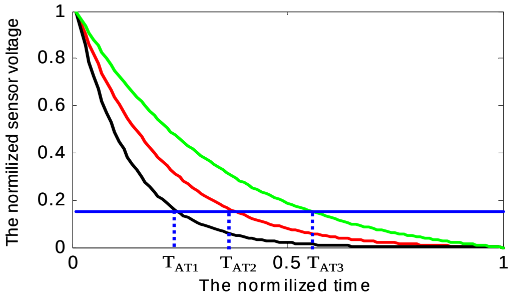


Fig. 3. Comparison of AT

The longer the attenuation time is, the lower the overall damping of the structure is, and vice versa. For the panel-type TPS structures, no matter the loosened location is a panel joint or a bracket joint, the bracket structure will be connected to materials of different damping, therefore result in the change of the attenuation speed of response signals. That's why the attenuation time is used as another feature of the sensor signals associating with energy to monitor the bolt loosening. Another important reason for using attenuation time as the feature is that this method is effective in computing and comprehensible. The time consuming process of solving equation set can be avoided and the attenuation speed of signals can be computed quickly in this method. Not only is the detection ability of the concerned parameters required, but also the rapid detection must be achieved for the future structure health monitoring system.

4 Experimental Testing

A structural health monitoring testing equipment was built to verify the proposed method, as shown in figure 4. A ribbed composite laminated panel was used as a substitute for the actual panel of the TPS; the size of the testing panel is 300 *mm* × 500 *mm* × 2 *mm*, and the thickness of the rib is 1mm and the length is 500 *mm*. To simplify the model of TPS, only two brackets were used to support the panel in experiments; thus not only can the actual structure be simulated, but also the influence of the disadvantageous factors can be weakened. An aluminous washer was manufactured referring to the model of reference [5], into which a $\Phi 6 \times 6mm$ column piezoelectric ceramics can be embedded.

Piezoelectric ceramics (PZT) were selected for this study because they are capable of performing as both passive and active sensor networks due to their high temperature endurance, high reliability and durability over other choices of sensors. The PZT-embedded sensor wash was placed between the base structure and the brackets, so it was integrated into the system without modification of the existing structure. In this configuration sensors can be protected from high temperatures and vibrations while also having enough sensitivity.

Fig. 4. The test setup to monitor the bolt loosening

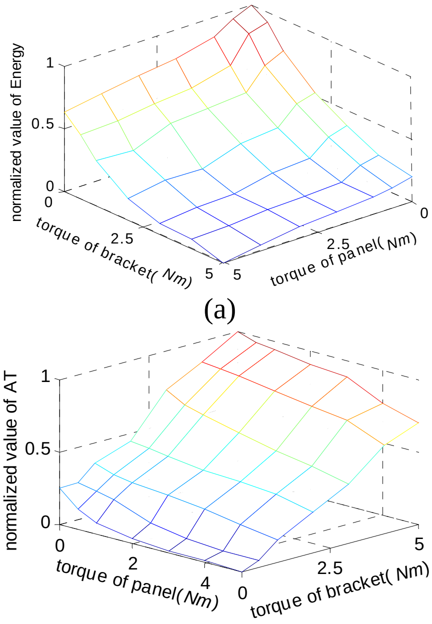
In this study a five-peak tone burst signal is applied to the actuator, as illustrated in figure 2. The advantage of tone-burst waveform lies in the fact is that it is compactly supported in both the time-domain and the frequency-domain. Therefore, it provides users with control over an input frequency, and also, allows a good resolution of signals in the time-domain, due to the reduced effect of dispersion. The excitation signal was generated by a waveform generator (Agilent 33120A), and amplified by a wideband power amplification electrocircuit; and the response signal was recorded by a Tektronix TDS5054B Digital Phosphor Oscilloscope. The function generator generates a transient five-peak input voltage signal and the input voltage applied on the PZT actuator according to the formula [17]:

$$V_{in}(t) = 20\left[H(t) - H(t - 5/f_c)\right](1 - \cos\frac{2\pi f_c t}{5})\sin 2\pi f_c t \qquad (5)$$

Where f_c is the central frequency and $H(t)$ is a *Heaviside* step function.

Seven torque levels on the bolts were defined in this experiment: 0 *N-m*(loosened), 0.5 *N-m* (hand-tightened), 1 *N-m*, 2 *N-m*, 3 *N-m*, 4 *N-m*, and 5 *N-m* (tight, perfect state). Two categories of experiments were completed to monitor the bolt loosening of the panel and bracket. In the first case, the PZT at point B was used as actuators and another PZT at point A acts as sensors, as shown in Fig. 1, making the bolt joints (C, D and E) of another bracket always tight whose torque levels are 5 *N-m*, so the tightness of bolts A and B represents the connecting condition between bracket and base structure, and the bolt tightness of bolt E represents the connecting condition of panel. In order to reduce the amount of experiments the levels of torque applied on the bolts of A and B were always the same, so there are seven kinds of torque levels for the bracket, and every kind of torque levels corresponds to seven kinds of torque levels of the panel joints. Finally there are forty nine kinds of experiments. The excitation voltage applied to the PZT was 20 *Volt* and the operating central frequency was chosen to be 155 *kHz*, which was experimentally determined to be the frequency whose signals were the most sensitive to the current torque levels.

It was found that no matter which bolt is tightened the amplitude of the response signals will decrease. The corresponding energy of different connection conditions can be calculated using equation (2), and the normalized results were given in figure 5(a). As revealed in the figure, the largest transmitted energy is obtained when both the panel and bracket joints are at the minimum torque levels, while the smallest amount of energy is recorded at the maximum torque levels. In other words, the energy is only transmitted in bracket when the bolted joints are completely loosened, so the recorded energy is highest; whereas the lowest energy is measured when the bolted joints are at standard torque levels, because a lot of energy is leaked and dissipated at bolt joints.



(a)

(b)

Fig. 5. Normalized value of short path transmission of composite laminate: (a) energy; (b) AT

The other feature, the AT, can be calculated using equation (3). The normalized result was given in figure 5(b). Result shows that the increase in panel torque levels will increase the attenuation speed of the sensor signals and decrease the AT, while the increase in bracket torque levels will decrease the attenuation speed and increase the AT.

For a specific panel/bracket-loosening status, the corresponding normalized values of energy and AT were measured to be 0.53 and 0.36 respectively. In order to quantify the torque levels of the bolts, the three-dimensional surface maps after spline interpolation were projected on the coordinate planes formed by torque levels of panel and bracket, so two contour plots were gotten, and the values of the extracted features form certain bands on the contour plots that correspond to the extracted energy and AT scalars. After the superposition of the contour plots, it is possible to narrow the two bands to a single zone as shown in figure 6, which indicates the diagnostic torque levels of the inspected bracket. In this example, the superposed position designates the bolts status to a panel torque of approximately 0.7–1.7 *N-m* and a bracket torque of 1.02–1.54 *N-m*. In this manner, a lot of statuses were verified to evaluate the accuracy of the algorithm, as revealed in Table 1. Most of the relative errors of estimation are less than 8%, where the relative errors are defined as:

$$\text{relative errors} = \left|\frac{\text{measured value - mean of estimated values}}{\text{measured value}}\right| \qquad (6)$$

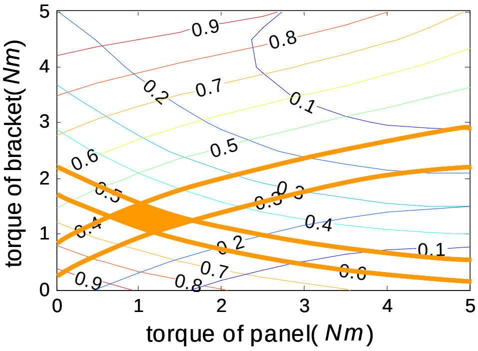
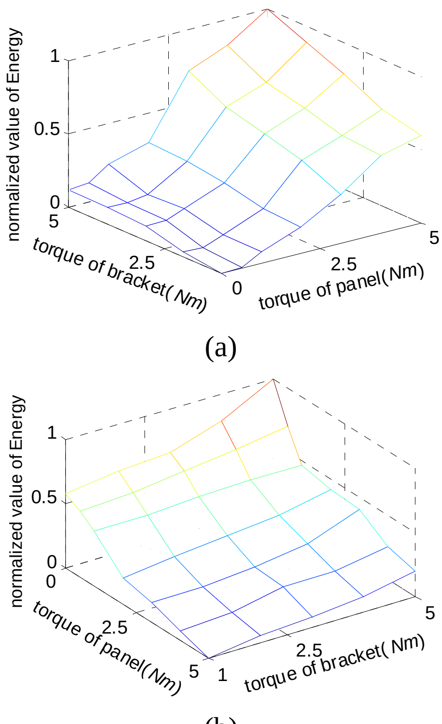


Fig. 6. The superposition of contour maps of energy and AT

In the second case, that is the long path transmission, the PZT at point B was used as actuators and another PZT at point C acts as sensors, as shown in Fig. 1. The tightness of bolts A, B, C and D represent the connecting condition between bracket and base structure. The selected torque levels for the bracket joint are 1 *N-m*, 2 *N-m*, 3 *N-m*, 4 *N-m*, and 5 *N-m*; the tightness of bolt E and F represents the connecting condition of panel, and the torque levels for the panel joint are seven levels as formerly defined, so there are thirty five kinds of experiments. To realize long path transmission, the excitation voltage was amplified to 200 *Volt* and the operating central frequency was chosen to be 135 *kHz*, which was experimentally determined to be the frequency whose signals were the most sensitive to torque levels. As revealed in the Fig. 7(a) and 7(b), the largest transmitted energy is obtained when both the panel and bracket joints are at the maximum torque levels which is opposite to Case 1, because the energy is mainly transmitted in bracket and panel, and only a few part is transmitted through base structure. However the surface map of AT is similar to Case 1.

Table 1. Estimation of bolt loosening levels

Case	Energy	AT	Measured T_p (*N-m*)	Measured T_b (*N-m*)	Estimated T_p (*N-m*)	Estimated T_b (*N-m*)	Relative Errors T_p (N-m)	Relative Errors T_b (N-m)
1	0.53	0.36	1.2	1.2	0.66-1.68	1.02-1.54	2.50%	8.75%
2	0.46	0.24	2.4	1.8	1.69-3.23	0.96-1.48	2.50%	5.00%
3	0.23	0.36	3.2	2.4	2.17-4.40	1.76-2.37	2.66%	5.10%
4	0.27	0.74	0.8	2	0.14-1.34	3.11-3.88	7.50%	3.75%
5	0.73	0.16	1.8	0.8	1.04-2.30	0.08-0.54	7.22%	9.37%
6	0.24	0.93	0.3	2.2	0.00-0.57	4.21-5.00	5.00%	2.16%
7	0.05	0.84	3	4	2.39-4.00	4.35-5.00	6.50%	5.69%

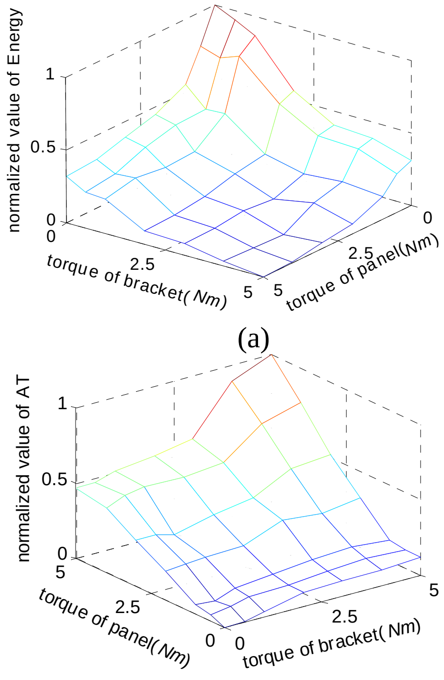


(a)

(b)

Fig. 7. Normalized value of long path transmission of composite laminate: (a) Energy; (b) AT

Same experiments were completed with ribbed aluminum plate substituting for the panel. The normalized results in this case were given in Fig. 8a and 8b, which are similar to the results of composite laminate panel: the minimum torque levels correspond to largest transmitted energy and the maximum torque corresponds to the smallest amount of energy. But the AT doesn't follow the rules; whichever bolts were fastened will increase the AT.

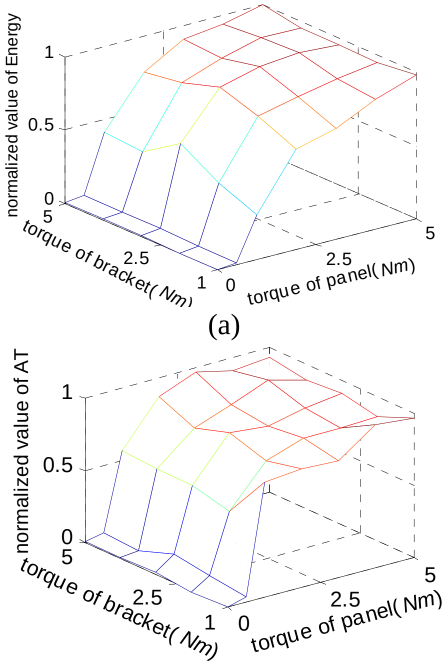


(a)

(b)

Fig. 8. Normalized value of short path transmission of aluminum panel: (a) Energy; (b) AT

Some different results were found from long path experiments on aluminum panel: the amount of received energy is determined by the connection condition of panel joints, as shown in Fig. 9a. The energy of the sensor signals rises rapidly with the increase of the torque levels when the torque is bellow 3 *N-m*, and approaches a constant when they are bigger than 3 *N-m*; while the torque of the bracket almost has no influence on the received energy. The variation of AT with torque levels is similar to that of energy. The former results of aluminum panel show that it's hard to identify the location of the loosening bolts when the damping characteristics of the base structure and the panel are close to each other.



(a)

(b)

Fig. 9. Normalized value of long path transmission of aluminum panel: (a) Energy; (b) AT

5 Conclusions

An improved analytical method based on the former works was proposed to assess the fastener integrity of a bolted structure, which uses energy and attenuation time as the extracted features. The reasons for improvement were also given, and studies show this method can be used not only to identify the location of loosening bolts rapidly, but also to estimate the torque levels of loosening bolts. It has been found that this method is simple with relatively low amount of computing, and the calculation rate rises greatly without impacting the accuracy of the results.

Two kinds of materials—composite laminate and aluminum are chosen for the ribbed panel to complete detection of bolts loosening in the typical panel-type TPS structure, and the experimental results of short path and long path transmission were analyzed and compared. In conclusion, the location and levels of loosening bolts can’t be estimated when the internal damping of the panel and washer are similar to each other; if the internal damping of the bracket is higher than that of the washer, but lower than that of the panel, the degree of bolts loosening as well as location can be evaluated and located rapidly by using energy and AT as the extracted features. Results of experimental measures show that most of the relative errors of torque degree estimated are less than 8%.

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