Design of a Hierarchical Health Monitoring System for Detection of Multilevel Damage in Bolted Thermal Protection Panels: A Preliminary Study

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Space vehicles perform in the temperature range from −160°C in space to 1650°C reached during reentry. As a result, space vehicles require high performance thermal protection systems (TPS) that provide high temperature insulation capability with lower weight, high strength, and reliable integration with the existing system. Carbon–carbon panels mounted with bracket joints are potential future thermal protection systems with light weight, low creep, and high stiffness at high temperature. However, the thermal protection system experiences a very harsh high temperature and aerodynamic environment in addition to foreign object impacts. Damage or failure of panels without being detected can lead to catastrophe. Therefore, knowledge of the integrity of the thermal protection system before each launch and reentry is essential to the success of the mission. Currently, the maintenance procedure of TPS is extremely time consuming and expensive due to its heavy reliance on human labor, which is also the largest obstacle in shortening the downtime of space vehicles after a mission. The objective of the study is to develop a built-in diagnostic system to assess the integrity of TPS panels as well as to lower inspection and maintenance time and costs. An integrated structural health monitoring system is being developed to monitor the TPS panels. The technology includes hierarchical investigation of the damages from loosening of bolts which connects TPS panels to the supporting structure, to potentially, identifying the location of damage on the panel caused by external impacts from micrometeorites and other objects. A prototype was manufactured and tested in an acoustic chamber which simulated a reentry environment to investigate the feasibility of the health monitoring system focusing on its survivability and sensitivity. The preliminary results were promising.

Keywords thermal protection system (TPS) · structural health monitoring (SHM) · acoustic chamber test · carbon–carbon panel

1. Introduction

Space vehicles experience harsh environments during the mission, which include high temperature gradients, aerodynamic acoustics, and impacts. Therefore, thermal protection systems (TPS) are necessary to protect space vehicles...
from these severe environments. However, TPS are also susceptible to damage during the mission, and these need to be repaired and replaced before the next mission [1,2]. The current maintenance procedure relies heavily on human labor, so it is extremely time consuming and expensive [3]. Maintenance is the largest obstacle in shortening the downtime of space vehicles after a mission. Therefore a new health monitoring technology 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. Furthermore, the role of structural health monitoring is critical in assuring the affordability of new advanced aerospace vehicles.

Typically, TPS consist of numerous TPS tiles and TPS panels applied externally to the outer skin and engine [4]. Carbon–carbon TPS panels have the highest temperature capability, so they are used in the nose cap and wing leading edge which reach the highest temperatures. Panel-type TPS also has an advantage in the ease of maintenance due to its mechanically fastened joints, compared to adhesively bonded joints of TPS tiles, which makes the maintenance and inspection of TPS tiles more difficult.

However, TPS panels face problems with mechanically fastened joints due to loosening of attachment during the mission as well as damage on the panels [5]. Accordingly, there exist many potential failure spots from mechanical attachment parts to the panel itself for the bolted TPS panel systems. In this study, all potential damage in a TPS panel is categorized into four levels based on damage location: (1) Loosening of base brackets; (2) Loosening of panels; (3) Impact events; and 4. Severe panel damages, as illustrated in Figure 1.

It is essential that a health monitoring system must be able to detect the damage in all four levels, which pose significant challenges in designing such a system. After extensive evaluations, an innovative hierarchical health monitoring system is proposed based on piezoelectric sensors/actuators networking to detect and monitor all four levels of damage. This paper summarizes the basic concept and approach of the proposed system in addition to the preliminary results of a prototype testing.

2. Approach

2.1 Sensor and Sensor Network Design

Depending on the input sources, the structural health monitoring systems can be divided into two types: active sensing systems with known inputs and passive sensing systems with unknown external inputs. An active sensing system excites the structure with internal actuators, and the sensors pick up the signals. For a passive sensing system, the input excitation are the external loads. Therefore the system is composed of sensors only, and sensor measurements are constantly observed in real time. For each monitoring part,
either an active or passive sensor network should be selected, depending on whether or not there exists an external load. To fulfill the multilevel health monitoring scheme for the TPS panels, both the active sensing network and the passive sensing network are required.

Piezoelectric ceramics (PZT) were selected for this project because they are capable of performing as both passive and active sensor networks due to their ability to play both roles as actuators and sensors [6]. Additionally, their high temperature endurance, high reliability and durability put PZT over other choices of sensors for this project. The location of the sensors is also important in the thermal protection system. While there exists a risk of damage to the sensors, better sensitivity can be achieved if the sensors are located close to the TPS panel. On the contrary, if the sensors are located away from the TPS panel, high survivability can be achieved at the sacrifice of decreased sensitivity. Therefore, sensors need to be well positioned to achieve both good survivability and sensitivity.

After numerous design evaluations, a PZT-embedded sensor washer was designed. Figure 2 illustrates the geometry and location of the PZT-embedded sensor washer in the TPS system. A pair of 6.35 mm (1/4 in.) diameter and 6.35 mm (1/4 in.) thickness PZT (APC 850) were embedded into the cylindrical washer. Then a thin wire layer was attached to the bottom of the PZT-embedded sensor washer to provide an electric connection to the external wires. Without modification of the existing structure, the PZT-embedded sensor washers can be successfully integrated into the system by placing the PZT-embedded sensor washers between the base structure and the brackets. In this configuration sensors can be protected from high temperatures and vibrations while also having enough sensitivity. Taking advantage of the characteristics of piezoelectric ceramics, a multilevel health monitoring scheme is feasible with these PZT-embedded sensor washers.

2.2 Selection of Signals and Sensing Configuration

Since the speed of elastic waves propagating in the TPS panels varies with the frequency of the excitation waveform, it is advantageous to use narrow-band signals that have narrow bandwidth in the frequency spectrum to minimize the effect of dispersion [7,8]. A windowed five-peak sine burst signal was used for this project. The frequency of the signal will be determined to characterize the defects most suitably for a particular monitoring task.

The 'pitch-catch' configuration was used for the inspection purpose of the TPS panels. The basic concept of this configuration is sending diagnostic waves from the actuators and receiving signals that characterize the defects at the sensors [9]. By putting the part to be monitored in the path of the diagnostic waves, the waves can deliver information about any changes in the system due to the defects. This change can be detected by comparing the signal with baseline data.

2.3 Hierarchical Health Monitoring System

The ability of the PZTs to perform as both sensors and actuators was utilized to achieve the four necessary sensing levels without having to
modify the current configuration. Level 1 can be accomplished by using one PZT in a PZT-embedded sensor washer as an actuator and another PZT in the same washer as a sensor (Figure 3 (a)). Therefore, the information about the loosening of base brackets can be extracted from the recorded signal which reflects the change of applied torque levels on the base brackets. For Level 2, ‘pitch-catch’ occurs within a bracket by using a pair of PZTs on one side of bracket as actuators and another pair of PZTs on the other side of the bracket as sensors (Figure 3 (b)). With this configuration, diagnostic waves propagate through the bracket, and will be affected by the loosening of the TPS panel. Unlike other sensing levels, Level 3 depends on external excitation sources. Hence, a passive sensing network should be used, while other sensing levels use active sensing network. The passive sensing network can be realized by using all of the PZTs as sensors (Figure 3 (c)). Level 4 is concerned with severe panel damages, and can be inspected by ‘pitch-catch’ between the brackets. Four PZTs in a bracket will be used as actuators, and another four in other brackets will act as sensors (Figure 3 (d)). An increased number of actuators will enhance the remote sensing capability, and at the same time, an increased number of sensors will improve the reliability of the health monitoring system.

3. Preliminary Test Results

Preliminary tests were performed for Level 1 and 2, and partially for Level 3. Signal generation, data acquisition, and signal analysis were done using the SMART suitcase by Acellent Technologies Inc [10].

3.1 Level 1: Base Bracket Loosening

Data was collected for three torque levels on the bolts: 1.13 Nm (10 in.lb), 3.39 Nm (30 in.lb) and 5.65 Nm (50 in.lb), and operating frequency was chosen to be 65 kHz, which was experimentally determined to be the frequency whose signals were the most sensitive to torque levels. This frequency is lower than the thickness-mode resonance frequency of the PZT due to the applied mechanical constraints on the PZT.

In Level 1, ± 50 V five-peak diagnostic waves are propagated from one PZT to another PZT within a PZT-embedded sensor washer as illustrated in Figure 4. Considering the short path between the actuator and the sensor relative to the dimension of the PZT, the early arriving part of signals contains the information of the torque applied to the bolts, and as a result, the first packet of arrived signals is of main concern. Figure 5(a) shows the change of amplitude in the first packet of signals depending on the torque applied on the bolt.

The relationship between the amplitude of the signals and the applied torque can be observed clearly by means of the power spectrum of the
windowed signals as shown in Figure 5(a). The power spectrum is defined by the sum of the voltages squared within the window. As shown in Figure 5(b), the power spectrum values increase as the torque applied on the bolt increases. Since the power spectrum values indicate the amount of transmitted energy, this phenomenon can be interpreted that more energy is transmitted from the actuator to the sensor when the bolt on a base bracket has higher torque. This output from the analysis is plausible, since the waves will be traveling through the interface of the PZT-embedded washer and base structure, and higher torque on the bolts will produce a stronger connection in the interface.

3.2 Level 2: Panel Loosening

For the Level 2, ‘pitch-catch’ occurs between two PZT-embedded sensor washers within a bracket. The $\pm 50$ V five-peak diagnostic waves start from actuators on one side of the bracket, pass by the bolt joint between the panel and bracket, and finally arrive at the other side of the bracket as illustrated in Figure 6. Therefore, the bolt loosening on the panel can be detected by investigating the signals recorded by the sensors. To enhance the penetration of the waves through the structure, a higher frequency than the one in Level 1 is desirable, and accordingly, 100 kHz was selected experimentally. The levels of torque applied on the bolts were 1.13 Nm (10 in.lb), 2.26 Nm (20 in.lb), and 3.39 Nm (30 in.lb).

As illustrated in Figure 7(a), the second packet of waves contains the information about the bolt loosening. This is because the second packet of signals represents the diagnostic waves passing through the bracket, while the first packet of signals are the waves passing through the base structure. Since the panel has direct contact with the bracket, but not with the bottom structure, it is the second packet that shows different amplitudes depending on the applied torque levels on the bolts.
The second packet of signals windowed by the square box in Figure 7(a) is quantified by calculating the power spectrum values. Unlike Level 1, the values of the power spectrum decrease as the torque level increases as shown in Figure 7(b). This phenomenon can be explained by careful investigation of the wave propagation path through the bracket. If the panel has contact with the bracket, part of the waves starting from the actuators will propagate into the panel through the interface instead of reaching the sensors. Therefore, the stronger connection caused by increased torque will cause more energy loss through the contact and as a result, less energy reaches the sensors.

3.3 Level 3: Impact Events

Given the external loads on the TPS panels, the passive sensing network can be activated to identify the source of the external loads. The passive sensing network can be realized by converting all of the PZTs into sensors [11]. To simulate the impact event, a preliminary test was performed using an instrumented hammer with a load sensor implemented. The monitoring system is triggered at the moment the panel is hit by the hammer. Sensors are distributed throughout the panel as shown in Figure 8, and all of them pick up the signals which characterize the impact, as shown in Figure 9. Through analysis of the obtained signals, the location and power of the impact can be identified. Analytical work on signal processing is a future task.

4. Experimentation and Verification

To test the feasibility and durability of the health monitoring system of the TPS panels, a reentry
environment was simulated in an acoustic chamber test at the Air Force Research Laboratory (AFRL) in Dayton, Ohio. The test focused on the sensitivity and survivability of the built-in health monitoring system. Figure 10 shows the overview of the acoustic chamber and the test setup. The test lasted for 15 min in the acoustic chamber at room temperature with the pressure waves at the magnitude of 135–140 dB in the frequency range from 50 to 500 Hz. The response of the panel was recorded by an accelerometer. Figure 11 plots detailed pressure input and out-of-plane acceleration of the panel in the frequency domain.

The TPS panel was inspected after the acoustic chamber test, both by hand and with the built-in health monitoring system, then compared with one another. In the harsh test environments of the acoustic chamber, none of 14 PZT-embedded sensor washers implemented on the TPS panel failed after the test. Therefore the prototype satisfied the survivability.

To check the sensitivity, three brackets with connections to the external terminal were investigated. Three inspected brackets are marked in Figure 10. Manual inspection of Level 1, which corresponds to the monitoring of both inside and outside bolts that connect the base structure and brackets, indicates that all of the bolts remained tight after the test. The results from the built-in health monitoring system also generated
consistent results by reporting that all 6 bolts remained tight within the level of accuracy. As for the results of manual inspection of Level 2, which is inspecting the loosening of the TPS panels from the brackets, the lower right bolt was remaining tight, the upper right bolt was slightly loosened, and the upper left bolt was missing. The analytical results from the health monitoring system successfully found the loose bolts and calculated the torque level accordingly.

5. Conclusion

A concept of hierarchical health monitoring system for detecting multilevel damage in bolted TPS panels was proposed. A PZT-embedded sensor washer was designed to realize the hierarchical health monitoring scheme which includes investigating the loosening of bolts and identifying external impacts and panel damage.

A prototype equipped with these PZT-embedded sensor washers was manufactured to investigate the feasibility of the health monitoring system. The prototype system was tested in an acoustic chamber which simulated a reentry environment, focusing on its survivability and sensitivity. The preliminary results from this test were very promising. The 14 PZT-embedded sensor washers survived this very violent test without incurring damage, and the health monitoring system successfully located loosened bolts in the prototype.

Future work includes design modification of the current PZT-embedded washers to enhance the sensitivity and survivability of the health monitoring system. The identification of external impacts and panel damage will be performed in addition to the investigation of the loosening of bolts. Advancement of the signal processing techniques will improve the accuracy of locating defects even further. With refined hardware and appropriate software, this health monitoring system has the potential to be applied to enhance the maintenance technologies of TPS panels.

References