# Structural Health Monitoring to Detect Fastener Failure

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## Summary

This paper presents experimental and analytical efforts focused on the development of structural health monitoring techniques to detect fastener failure. A realistic thermal protection system component and an aluminum plate demonstration article have been investigated. Vibration analysis techniques are utilized with structural health monitoring classifier features based on spectral functions. Features are identified using an automated process based on statistical pattern recognition methods. Efforts are focused on detecting, localizing, and assessing damage resulting from loose or missing fasteners.

## Introduction

To reduce costs and meet turn-around goals of future space launch vehicles, an automated system is needed to assess the health of the entire structure within hours of the completed mission. Structural health monitoring (SHM) refers to automated methods for determining adverse changes in the integrity of mechanical systems[1]. The structure under investigation is excited and the response to the loading is sensed at various locations throughout the structure. Signal are collected and processed, and the state of the structure is diagnosed.

In the literature, the capability of SHM systems is typically broken down into the following levels of increasing difficulty: (1) damage detection; (2) damage localization; (3) damage assessment; and, (4) life prediction. Damage detection refers simply to the ability to detect whether or not a structure is damaged. For damage localization, the region of the structure with damage is identified. The next level is to assess the severity of the damage. The last level is to predict the remaining life of the structure.

Structural health monitoring techniques applied to a realistic thermal protection system (TPS) assembly are discussed in the following section. These studies are focused on detecting and locating loose bolts in the assembly. In a subsequent section, studies on assessing the degree of damage based on loss of fastener preload in an aluminum plate demonstration article are discussed. These studies build on the TPS assembly studies to include assessing the damage severity in addition to detecting and locating damage.

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**Thermal Protection System Studies**

A carbon-carbon panel provides the basis for the TPS assembly shown in Figure 1. The panel is approximately 24.0 in (61.0 cm) by 24.0 in (61.0 cm) by 0.125 in (3.18 mm) thick and is bolted to 15 evenly spaced brackets, which in turn are bolted to a titanium 0.100 in (2.54 mm) thick ribbed backing structure with 0.667 in (16.94 mm) thick ribs. The structural condition of the panel is determined by the torques on each of the 15 fastening bolts. When all bolts are fully tightened, the panel is *healthy*. A bolt loose condition, obtained by loosening a bolt approximately a quarter turn, corresponds to a *damaged* state. Four piezoelectric transducers are attached to the side of the backing structure corresponding to the inner fuselage of the aerospace vehicle, where temperatures will remain within the operating range of the transducers.

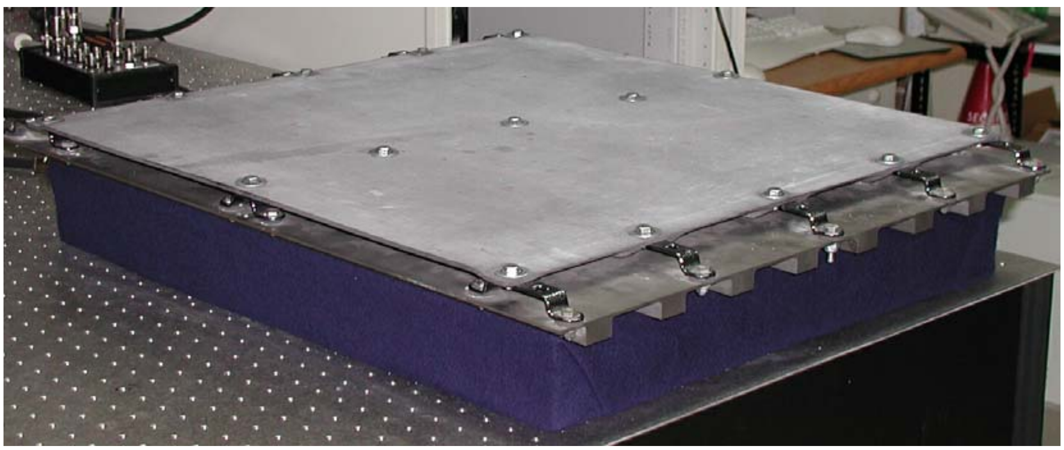

Figure 1. Thermal protection system assembly

For the experimental testing, an excitation signal is sent to one piezoelectric using a swept frequency sinusoid, ranging from 0-7000 Hz over 1.0 second. The vibration responses are recorded from the remaining three piezoelectrics. Features with the ability to discriminate between damage conditions are identified based on (cross) power spectra, transfer functions, and coherence functions. A visual search for features can be extremely time consuming, so the automated process shown in Figure 2 has been implemented. The problem is broken down into a series of two class problems and intervals of contiguous frequency bins are considered. Classification is accomplished using a single discriminant function for each structural state. The discriminant functions are derived from the multivariate Gaussian class-conditional probability density function. Features are screened based jointly on correlation with class label and lack of correlation with each other. A sequential floating forward select method [2] is used for feature selection to provide a subset of measurements from the feature pool.

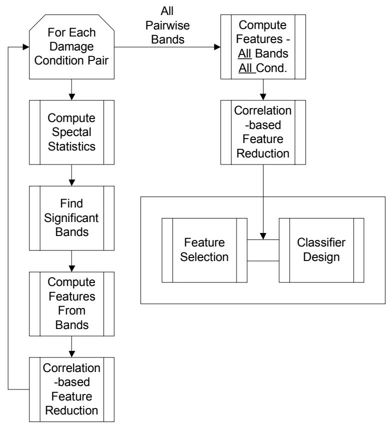


Figure 2. Automated process to generate candidate features

Exploiting information about the physical structure is essential for long-term success of any SHM system. A finite element model of the TPS assembly has been created using shell elements for the TPS panel, brackets, and backing structure. Analytical modal dynamics simulations have been performed to duplicate, as closely as possible, experimental testing. Results from the finite element analyses provide useful information regarding the overall structural dynamics and features used for the SHM classifier. Figure 3 shows a comparison between measured and predicted time and frequency signals for the healthy structure. Note that the response is dominated by higher frequency content. To accurately detect damage due to a loose bolt, it is critical to identify those modes which respond well to the excitation, yet are significantly influenced by the fastener conditions. The analyses predict relatively high response at an analytical mode around 6417 Hz. However, as shown in Figure 4, the majority of the strain energy remains in the backing structure for this mode. It is unlikely that measurements at this frequency would significantly aid in detecting a loose bolt.

To evaluate the accuracy of the SHM system, test results are accumulated across "held out" rounds from the classifier design process. One round corresponds to replicates of each loose bolt condition and the healthy condition. The average accuracy across all the tests is 99.1%. The lowest accuracy for a given round is 96%. The probability of a false alarm (declaring a loose bolt given a healthy system) is 0.2% and the probability of a missed detection (declaring a system healthy given a loose bolt) is 0.3%. Therefore, the probability of correctly declaring damage for any loose bolt condition is 99.7%.

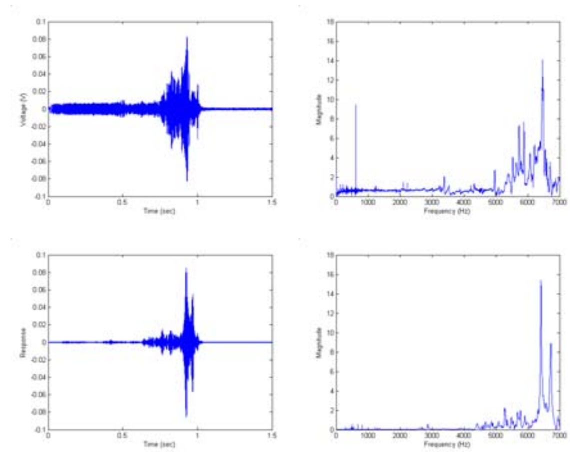

Figure 3. Comparison of time and frequency signals from experimental testing (top) and finite element analysis (bottom) of healthy structure

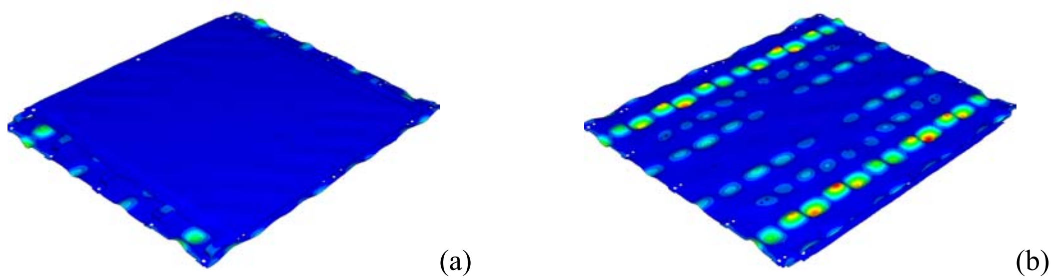


Figure 4. Displacement fringes for analytical mode at 6417.1 Hz viewed from top of TPS panel (a) and bottom of backing structure (b)

**Aluminum Plate Studies**

To extend the structural health monitoring techniques to include damage assessment, investigations have been performed using the aluminum plate demonstration article shown in Figure 5. The plate is approximately 12.0 in (30.5 cm) x 12.0 in (30.5 cm) x 0.200 in (5.08 mm) thick and is fastened to an optical table through four bolts located near the corners of the plate and 0.5 in (1.27 cm) from the plate edges. When all bolts are fully tightened, the panel is *healthy*. A bolt loose condition corresponds to a *damaged* state. Unlike the TPS studies, where each bolt was uniformly loose, in the aluminum plate studies degrees of bolt looseness are considered. Four piezoelectric transducers are attached near the corners of the plate and approximately 4.0 in (10.16 cm) from the plate edges.

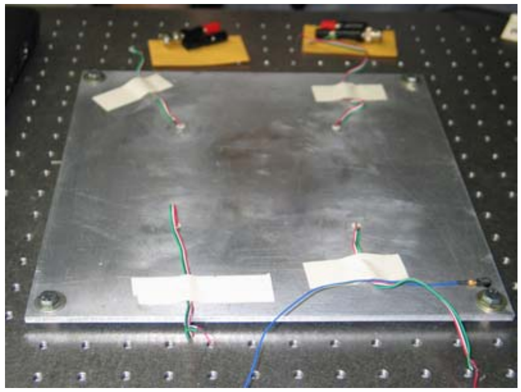

Figure 5. Aluminum plate demonstration article

For the experimental testing, an excitation signal is sent to one piezoelectric using a swept frequency sinusoid, ranging from 0-1500 Hz over 1.0 second. The vibration responses are recorded from the remaining three piezoelectrics. Features with the ability to discriminate between damage conditions are identified based on (cross) power spectra, transfer functions, and coherence functions. The automated process shown previously in Figure 2 is used for feature identification. Classification is accomplished using a single discriminant function for each structural state, where the structural states include four torque levels at each of the bolts. The discriminant functions are derived from the multivariate Gaussian class-conditional probability density function. A sequential floating forward select method is used for feature selection. Ongoing experimental data collections will provide a comprehensive set of representative training data for the classifier.

As with the TPS studies, exploiting information about the physical structure is essential for long-term success. A finite element model of the aluminum plate demonstration article has been created using shell elements. Analytical modal dynamics simulations have been performed to duplicate, as closely as possible, experimental testing. Figure 6 compares measured and predicted time and frequency signals for the healthy structure. Note that the analyses capture the general trends seen in the experimental response. Differences between the measured and predicted responses can be attributed to numerous factors including discretization error at higher frequencies, damping present in the various modes, noise in the experimental data, and uncertainty regarding the precise location of the sensors on the physical test article. An innovative modeling technique to simulate bolt damage states has been developed. Using this technique, analyses can be performed to simulate various levels of torque at each of the fasteners. Analytical efforts are continuing and will be instrumental in providing a physics-based understanding of selected features used in the damage detection algorithms.

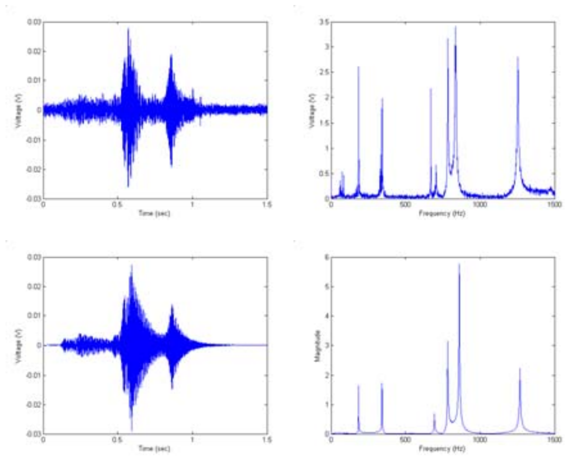

Figure 6. Comparison of time and frequency signals from experimental testing (top) and finite element analysis (bottom) of healthy structure

## Conclusions

A SHM system has been developed to detect and locate fastener damage in a TPS assembly. The overall localization accuracy of the SHM system on test data is 99.1% with 99.7% probability of detecting a damage condition at a 0.2% probability of false alarm. Finite element modeling techniques have been developed to enable analytical simulations to closely duplicate the SHM experimental testing. The analytical simulations are instrumental in providing a physics-based understanding of the selected features and ultimately predicting the remaining life of the damaged structure.

The development of a SHM system to detect, locate, and assess fastener damage in an aluminum plate demonstration article is underway. An automated process is used to identify initial features. Final feature selection for the classifier is based on statistical pattern recognition methods, with the structural states to be identified based on the torques on each of the four fastening bolts. Finite element analyses, utilizing an innovative bolt modeling technique, provide a physical interpretation of selected features.

## References

1 Sohn, H. and C. Farrar, "Damage Diagnosis Using Time Series Analysis of Vibration Signals," *Smart Materials and Structures*, Vol. 10, pp. 1-6, 2001.

2 DeSimio, M., I. Miller, M. Derriso, K. Brown, and M. Baker, "Structural Health Monitoring Experiments with a Canonical Element of an Aerospace Vehicle," *Proceedings of the 2003 IEEE Aerospace Conference*, Big Sky, MT, March 2003.