New Processing to Detect and Track Damage in an Aerospace Wing Attachment Fitting

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ABSTRACT

This paper demonstrates the ability to design health monitoring systems from a systematic perspective and, with proper sensor and actuator placement, to detect and track damage occurring in a structure. The results from the first of three separate tests were previously presented showing the daily progression of damage until ultimate failure of the part under test. The tests were performed and the data were collected to emulate on-ground health monitoring scenarios. The data indicate the precursors to total structural failure significantly before the failure occurs. In this paper a different processing method will be presented and compared to the original method.

To achieve these results, a design optimization was performed to determine the best locations to excite the structure and to collect data while using the minimum number of sensors. The techniques used to design the monitoring system allow for any type of sensor (thermal, strain, electromagnetic, etc.) and can find the optimal locations with respect to defined objective functions (sensitivity, cost, etc.). They also account for modeling error and variations in boundary conditions. The use of model-based optimization techniques for the design of the monitoring system is driven by the desire to obtain the best performance possible from the system given what is known about the system prior to implementation. The use of a model is more systematic than human judgment and is able to take far more into account concerning the dynamical response of a system than even an experienced structural engineer.

1 DAMAGE DETECTION SYSTEM DESIGN

Miltec Research and Technology (MRT) was asked to participate in the Air Force Research Lab's (AFRL) fatigue test of a fitting from a 3-node center wing panel. On a typical aircraft the fitting connects the outer wings to the center wing. In the past few years, many aircraft have developed fatigue cracks in the center wing box fittings. Currently, in order to detect the existence of cracks in the fittings, eddy current non-destructive inspection technology has been used on a scheduled basis. The disassembly of the wing and inspection of the fitting is a labor intensive process that is sometimes unnecessary because no damage developed during the inspection interval. In general, maintainers would like to move from a costly interval inspection based paradigm to one of condition based maintenance (CBM). A CBM system's goal is to determine the equipment's health and to act only when maintenance is actually necessary thus minimizing spare parts cost, system downtime and overall time spent on maintenance.

The purpose of the test was to demonstrate the ability to design health monitoring systems from a systematic perspective and, with proper sensor and actuator placement, to detect and track damage occurring in a structure. To this end, a design optimization was performed to determine the best locations to excite the structure and to collect data while using the minimum number of sensors(Frazier and Parker, 2004). The type of sensors used in this case was a uni-axis accelerometer. It should be noted that the design algorithms used here are not limited to accelerometers. They allow for any type of sensor (thermal, strain, electromagnetic, etc.) as long as mathematical models are provided and they find the optimal locations with respect to user-defined objective functions (sensitivity, cost, etc.) (Danny Parker and Cuevas, 2006). The use of model-based optimization techniques for the design of the monitoring system is driven by the desire to obtain the best performance possible from the system given what is known about the system prior to implementation. The use of a model is more systematic than human judgment and is able to take far more into account concerning the dynamical response of a system versus an experienced structural engineer. It is understood in the context of structural modeling that all models have errors and that good designs produced by model-based techniques should be tolerant to these errors. Demonstrations performed by MRT in the past have shown

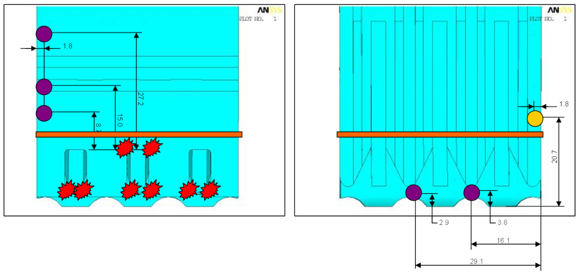

Figure 1: Optimal Sensor Design: Sensors (purple), Actuator (yellow), Hotspots (red), and Failure Location (orange)

that poorly placed sensors can be very insensitive to damage development(Frazier and Parker, 2003).

A multi-objective genetic algorithm (GA) was employed to perform the optimization. The foundations of this method are presented in(Rinehart, 2005). The objectives of the optimization were:

1. be highly sensitive to damage occurring in potential 'hot spots',
2. maintain adequate ability to detect damage occurring elsewhere in the structure and
3. maintain robustness to modeling errors.

Because of the size of the search space and the computational costs associated with evaluating the objective functions, the GA was implemented on a 16-core parallel computing cluster. Each individual in the GA was evaluated on its own core and the total optimization time was approximately 3 weeks. When the GA completed it produced a set of optimal designs using 3 to 6 sensors and 1 or 2 actuators. These designs were simulated (time-domain) to assess their performance. The simulations tested the design's sensitivity to damage occurring at each of the hot spot locations plus a random location. After evaluating the different designs, a 5-sensor and 1-actuator design was chosen to implement in the first test with the expectation that a 3-sensor design would be used for the second test. For further information about the optimal design techniques used here the reader is referred to (Rinehart, 2005; Danny Parker and Cuevas, 2006; Frazier and Parker, 2004; Frazier and Parker, 2003)

Figure 1 shows the location of the sensors (purple) and actuator (yellow) on the wing fitting. Also shown in Figure 1 are the hot spots (red) where the system was designed to be highly sensitive damage occuring there and an orange bar showing where the fitting ultimately failed by breaking in two. The wing fitting used in this test were taken from wing sections of aircraft that had been in-service. The specimen measured approximately 2 m tall and 0.5 m wide. They included the skin panel, three stiffeners, and a U-channel fitting.

The fitting was cycled at 4 Hz with loads having spectra that approximated flight load conditions. The goal was to induce a stress crack in the component.

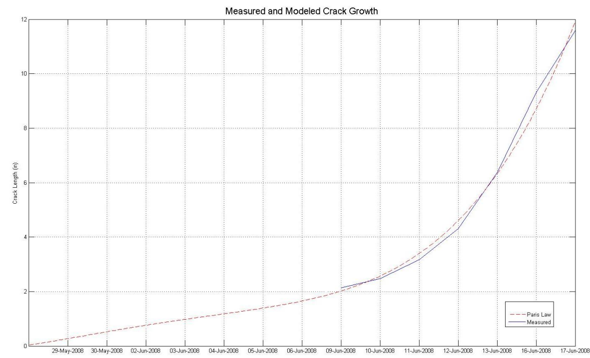

Figure 2: Measured and Paris Model Skin Crack Length Measured (blue), Paris Law (red)

The first crack found was approximately 5.44 cm long and the panel had endured 1,161,224 cycles over 8 days at that time. However, due to the extended length of this crack and that it occurred away from the initial area of interest, the crack is now thought to have initiated earlier. The test continued, and every day the cracks were measured and photographed. Figure 2 shows the measurement of the predominate crack in the skin panel. Figure 2 also shows the fit of a Paris Law type model to estimate the crack length over the entire testing period. This was the dominate failure mode. However, this was not the only damage present in the structure. The data discussed later are a measure of the total damage present in the structure and not just the dominate failure. Complete failure of the panel occurred at 1411 hrs of fatigue cycling. The specimen was removed from the load-frame and submitted to AFRL for failure analysis. It should be noted that the component did not fail where the damage was expected to occur.

2 DAMAGE METRICS

The original experiment was conducted using the damage metric developed in (Frazier and Parker, 2003). It can be summarized as removing the mean from the time series and then computing the covariance matrix (Q_y) of the time series from the sesnors. That covariance is then compared to a reference covariance (Q_{base}). The original damage metric is calculated as

$$DM_{original} = \|Q_{base} - Q_y\|_2 \quad (1)$$

The new metric is one that is straightforward. It is essentially the 2-norm of the ratio in the transfer functions of the systems at different times. In the frequency domain it is defined as

$$DM_{new} = \sum_{i=1}^{\#sens} \int_{f1}^{f2} \left\| \ln \left(\frac{H_i(f;t)}{H(f;t_{ref})} \right) \right\|_2 df \quad (2)$$

where the sum is over the number of sensors and the integral is over the frequency range of interest.

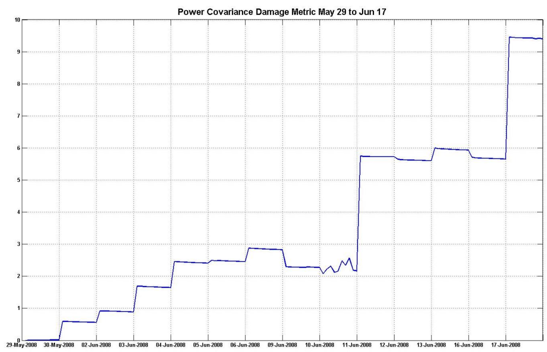

Figure 3: Original Damage Metric

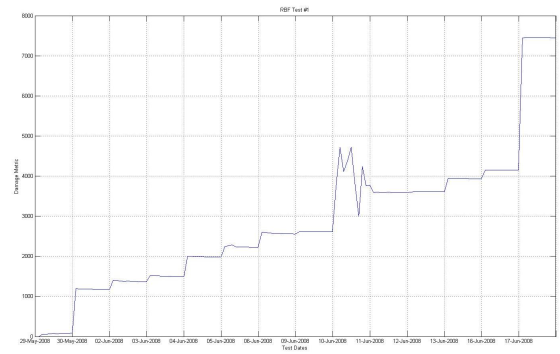

Figure 4: Log Ratio Damage Metric

3 METRIC COMPARISON

During the first component test the sensor-actuator placement strategy was evaluated using five accelerometers and one piezoelectric actuator. The frequencies used by the monitoring system to excite the structure were 500 - 6000 Hz. Each test consisted of collecting 10 seconds of data and 10 consecutive tests were run each day. The baseline data used in this experiment is the first set of data taken on 29 May.

Figure 3 shows the results when the data are processed using the original damage metric. The data illustrate a general trend of damage growing daily followed by a large jump in the damage metric the day before the part ultimately failed. Since the structure being monitored was undergoing an accelerated life cycle test and thus damage was increasing every day, the results are consistent with expectations. There was a large increase in the variance of the measurement taken on 10 June. Since all subsequent readings returned to normal it was concluded that an undocumented condition was present on 10 June that caused the increased fluctuations. MRT was not present during any of the testing and can not definitively explain these discrepancies but the data was left in the plot for consistency's sake. The salient feature of the graph for this discussion are that the damage metric is not monitonically increasing even though it is assumed that the fatigue test is causing more damage. In general there should be no expectation of a purely monotonically increasing damage metric because process noise is always present. Instead the overall trend should be analyzed and more consideration should be given if the damage metric has consistently increased instead of a spurious increase. However, it was decided to see if different signal processing would more closely match expectations. For a more complete discussion of the relavent feature of the damage metric as it pertains to the fatigue test refer to (Parker, 2009).

Figure 4 is the same data processed using the method described in eq. 2. The frequencies which were integrated over were chosen to cover the bandwidth that the input signal generated. This is a key difference between the Log Ratio metric and the orignal metric. The orignal metric operated on the time series so there was no effective way of choosing particular frequency ranges. Figure 4 is much more in line with what one would expect from a fatigue test since it does increase daily. Still, it has a solid trend with increasing damage severity and exhibits a dramatic jump prior to complete failure. In fact, this corresponds to one day prior to failure. One possible drawback to this metric is that it tends to ignore relative changes, i.e., frequencies near modes (where the response is large) carry the same weight in the sum as frequencies near zeros (where the response is low). This metric can be easily be modified to accommodate the use of coherence estimates, but it has not been performed in this case since coherence estimates can be poor when the actual coherence is low. It should be noted that by processing the data in this manner the damage metric was more sensitive to whatever fluctuations cause the 10 June anomoly. The Log Ratio metric seems to indicate that the original metric lost sensitivity to increasing damage during the period 11 June through 13 June. Of course, this is just one examination and it is possible the original metric may perform better on another data set.

4 USES WITHIN CBM FRAMEWORK

Questions may arise asking at what damage metric value the user should become concerned that there is an issue with the structure. If an absolute threshold is desired to determine when maintenance should be performed, a series of experiments would have to be conducted to determine what that threshold should be. Each time this method was applied to a different structure a new set of experiments would need to be conducted to determine the appropriate threshold. However, if the desire is to use a system such as this to generate a "reason-to-inspect" condition for a CBM philosophy, there are a few ways to look at the data without using absolute thresholds. One way is to look at the statistical probability that the structure being monitored has changed. This would allow a maintainer to know with a prescribed amount of certainty that there is a change in the structure. In this experiment it was determined by 30 May using statistical methods that there was a much greater than 99.999999999% probability that the structure had developed damage. Another, perhaps more useful way to make decisions based on the damage metric, is by trend analysis. The damage metric can be monitored to watch how fast it is increasing and for large jumps. Applying this in a rudimentary way for the data shows that the damage is increasing at a constant rate up until 9 June, and then on 11 June there was a significant change. If inspection had been done at this point a 7.6 cm crack across the skin would have been found along with cracks starting to form on the attachments between the stringers and the skin. Over the next three days the damage metric stayed relatively constant. Then on the day before ultimate failure another large change in the damage metric occurred. If an inspection had been done at this point it would have revealed that there was almost no strength left in the structure.

5 CONCLUSION

A health monitoring system was designed using systematic methods. It was designed such that the system was optimized to have a minimal number of sensors and be sensitive to damage occurring on a center wing panel in both expected and unexpected locations. With these methods, structural health monitoring systems can be designed using any combination of strain, vibration, thermal, or electromagnetic sensors with the purpose of having maximum sensitivity to damage occurring in known or unknown locations on a structure.

Data from the designed system were collected and signal processing was applied to create a damage metric. This paper compared an original damage metric to a new one. There is no way to say that one is distinctly better than the rest given that there was only one test, but the new metric does line up better with expectations of how damage grows. It is left up to the reader to decide if that expectation is correct. The new metric also appears to have greater sensitivity; not just to the 10 June anomaly, but also to the large jump the day before ultimate failure, which increased from 66.7% in the original to 87.5% using the Log Ratio method. Again this is only one experiment, but it does show cause for further investigation.

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