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A Design of Experiments Approach to Determing Structural Health Monitoring Sensor Durability

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Abstract: Structural Health Monitoring (SHM) promises to decrease the maintenance cost and increase the availability of aging aircraft fleets by fundamentally changing the way structural inspections are performed. But this promise can only be realized through the consistent and predictable performance of a SHM system throughout the entire remaining life of an aircraft. Questions remain concerning the performance, durability and reliability of SHM systems after long-term exposure to the hostile aircraft environment. These questions have been a serious impediment to the large-scale implementation of SHM on legacy fleets. This study uses a design of experiments (DOE) approach to develop a systematic method to determine the durability and performance of a PZT-based SHM sensor subjected to aircraft environmental factors.

Keywords: Structural Health Monitoring, Sensor Durability, Design of Experiments

1 Introduction and Background

Durability of a Structural Health Monitoring system is critical to its viability as a tool to reduce the cost and burden of recurring aircraft structural inspections. Many studies have addressed the installation of SHM systems as a means to improve or replace the current inspection paradigm on legacy and future aircraft [Boller (2000); Boller (2001); Goggin, et al. (2003); Ikegami and Haugse (2001); Malkin, et al. (2007)]. But while SHM technologies continue to advance, SHM systems have yet to gain a foothold on the flightline of an aging aircraft fleet. The good safety record of the current inspection paradigm, combined with uncertainties in SHM affordability, capability and maintainability, contribute to the lack of widespread SHM implementation [Achenbach (2007); Derriso, et al. (2007)].

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In order for SHM systems to gain acceptance, a greater understanding is needed of how a given SHM system will be affected by aging in the aircraft environment. Additional research is required to determine the effects of thermal/mechanical cycling, electromagnetic interference, various aircraft fluids, etc. (see [Chambers, et al. (2006); Kessler (2005)]) on SHM technologies. Research is also needed on how identified effects can be mitigated or at the very least, taken into account. The objective of this research is to use a common technology in SHM research as an example of how to design and implement a durability experiment to determine and be able to predict the performance of a SHM sensor subjected to aircraft environmental factors.

2 Causes of SHM Sensor Signal Changes

Unfortunately, structural damage is not the only event that can cause the signal interpreted at the catch transducer to be different from the initial baseline signal. Blackshire et al. showed thermal cycling has a detrimental effect on PZT performance due, at least partially, to the differences in thermal expansion between the PZT and the substructure causing cracking and/or disbonding of the PZT. [Blackshire and Cooney (2006)]. Similarly, Chambers reports peak voltage differences of up to 40% after exposure to thermal shocks, humidity or water-based fluids for a PZT-based SHM sensor [Chambers (2006)].

A cause and effect diagram, see Figure 1, has been developed to identify the potential causes for changes in SHM sensor signals from intended (structural damage) and unintended (system failure, etc.) factors.

Performing a similar analysis on sensor degradation and sensor failure provides insight into the potential causes of signal changes due to changes in the sensors rather than changes in the aircraft structure. Environmental factors that may cause SHM sensor changes can be found in existing aircraft component reliability specifications such as MIL-HDBK-781, Handbook for Reliability Test Methods, Plans and Environments for Engineering, Development Qualification, and Production [Department of Defense (1996]; MIL-STD-810, Test Method Standard for Environmental Engineering Considerations and Laboratory Tests [Department of Defense (2000)]; MIL-STD-461, Requirements for Control of Electromagnetic Interference Characteristics of Subsystems and Equipment [Department of Defense (1999)]; and RTCA/DO-160, Environmental Conditions and Test Procedures for Airborne Equipment [RTCA (2005)]. The latter document is recommended by the FAA for aircraft environmental standards. Figure 2 presents a cause and effect diagram for SHM sensor degradation or failure using the environmental test conditions provided in the documents listed above.

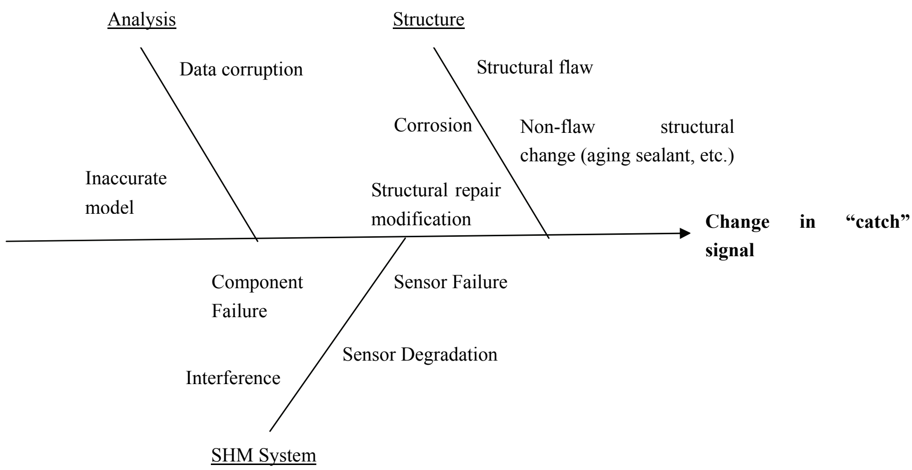


Figure 1: Changes in sensor signals can result from a wide range of factors

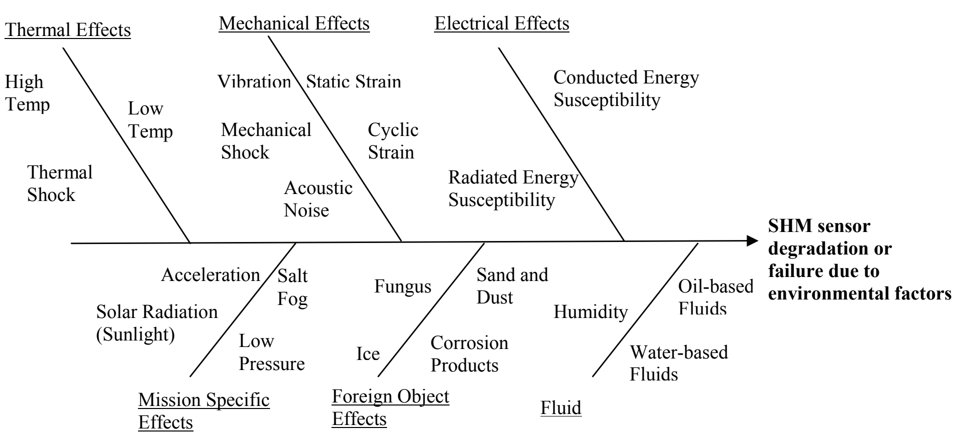


Figure 2: Aircraft environmental factors potentially affecting SHM sensor performance

3 Experimentally Determining the Effects of an Environmental Factor

This research uses guided wave technology as the baseline. Figure 3 shows a general guided wave SHM method using "pitch" and "catch" transducers attached to the surface of the structure being monitored. The pitch transducer excites elastic waves in the structure which propagate along the surface and can be detected by the catch transducer. Initial readings of the undamaged structure establish a signal baseline at the catch transducers. Structural damage that occurs between the pitch and catch sensors changes the characteristics of the wave as it moves across the surface, and that damage can be identified by the differences between the received signal and the initial baseline reading [Giurgiutiu, et al. (2001); Mi, et al. (2006)].

The baseline "SHM system" for this experiment consists of sensors and signal excitation/data collection equipment. Each sensor consists of one pitch-catch pair of piezoelectric lead ziconate titanate (PZT) transducers attached to a 0.125 inch thick 6061-T6 aluminum test specimen. Signal excitation and data collection is performed with a arbitrary waveform generator and a 2.5 MHz data acquisition card respectively, both controlled in a LabVIEW®environment. PZT disks were chosen as the system sensor due to their low cost and proven ability to effectively generate guided waves in thin plate structures [Mi, et al. (2006); Underwood, et al. (2008)]. Figure 4 shows a sample test specimen and the sensor excitation / data collection equipment.

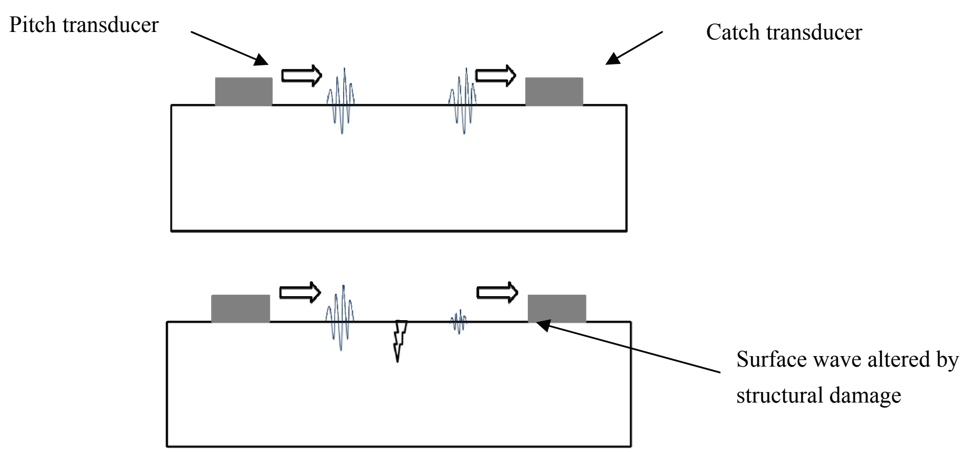
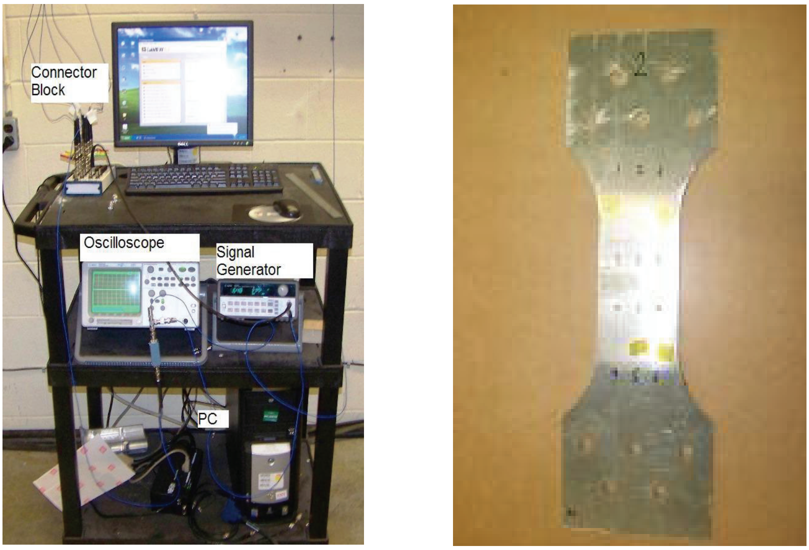


Figure 3: Structural damage causes changes to surface waves detected by guided wave SHM systems

As noted above, several publications have noted the effects of particular environmental factors on PZT signal, but since analysis of the statistical significance of the signal changes is not the focus of the studies, it is normally not accomplished [Blackshire and Cooney (2006); Underwood, et al. (2008); Chambers (2006); Kessler(2005)]. To determine the statistical significance of these changes, a design of experiments approach is proposed, starting with the general guidelines provided in Montgomery [Montgomery (2005)].



(a) Test Equipment (b) Example Test Specimen

Figure 4: LabVIEW®Controlled Sensor Excitation and Data Collection on Aluminum Test Specimens

1) Recognition and statement of the problem
2) Selection of the response variable
3) Choice of factors, levels and ranges.

To limit the scope of the experiment, the experimental design will focus on the static and cyclic strain environmental effects listed in Figure 2. The problem statement: Determine if statistically significant changes in PZT sensor response occur due to successive applications of static and cyclic strain.

For this experimental design, the response variable is the “Integrated Amplitude” of the signal detected at a catch PZT as shown in Figure 3. The response variable is calculated by taking the square root of the sum of the squares of the signal amplitude over a defined time-of-flight window. The response variable calculation and windowing techniques are further described in Underwood [ref].

Two types of experimental factors are considered in this design: potential design factors and potential nuisance factors. Table 1 lists the potential design and nuisance factors.

Paired t-tests will be performed to determine significant changes in the response variable. The following hypotheses will be tested:

Table 1: Factors used to build the SHM durability experiment

Potential Design Factor	**Potential Nuisance Factor**
Glue type	Sensor Installation variability
Sensor excitation frequency	Specimen material variability
Static strain level	Data collection system variability
Cyclic strain level	Test apparatus variability
Number of strain cycles	Test environment variability

Table 2: Null Hypotheses to be Tested

Hypothesis Set	**General Null Hypothesis**
S1	Average baseline sensor response is equal for 2 glue types
S2	Average baseline response does not change after applying a predefined static strain
C1	Average baseline response does not change for a given glue type after applying a predefined number of cycles at a predefined strain level
C2	Average sensor response is equal for 2 glue types after applying a predefined number of cycles at a predefined strain level

Levels of the potential design factors must be established to determine the structure of the experiment. Two glue types will be used in a manner similar to Blackshire, where several glue types were used to attach the PZTs to the test specimens in order to compare performance [Blackshire and Cooney (2006); Blackshire, et al. (2007); Martin and Blackshire (2007)]. One type to be used will form a "stiff" bond between the PZT and the test specimen and one will form a more "compliant" bond. Sensor excitation frequency will be held constant throughout the testing.

The sensor sample size and the number of static strain levels can be determined using the method given in Montgomery [Montgomery (2005)], where a desired "significant" change in the value of a response variable is selected, and the sample size and number of levels of the experimental factors are iterated such that if the difference between any two treatment means exceeds a specified value, the null hypothesis should be rejected.

The method uses "Operating Characteristic, (OC)" curves generated from a non-central F distribution that plots the probability of committing a Type II error, β, against a parameter Φ [Montgomery (2005)], where:

$$\Phi^2 = \left(\frac{naD^2}{2b\sigma^2}\right) \tag{1}$$

with:
n = Sensor sample size
a = Number of levels of the “glue type” factor
b = Number of levels of the “static strain” factor
D = Change in response variable determined to be significant
σ = estimate of the response standard deviation

Montgomery recommends fixing the values of a, b, D and σ in equation 1 at desired levels and iterating n to determine various values of Φ^2. OC curves can then be used to determine the corresponding value of β for each sample size. Selecting the desired level of β then determines the needed sample size.

The number of levels of the “glue type” factor is set at two, the stiff glue type and the compliant glue type. Estimates for D and σ for this experimental set-up derive from experiments performed by Underwood to determine the change in PZT pitch-catch response due to an induced crack in the test specimen [Underwood, et al. (2008)]. Underwood found a 15 mV decrease in integrated response amplitude between pitch-catch PZTs when the signal passed over a fatigue crack. Results also show an integrated response amplitude variation of approximately 5 mV when signals are repeatedly passed between pitch-catch pairs no fatigue crack present. Based on these initial tests, a change in response variable greater than 10 mV is considered significant, with a signal standard deviation of 5 mV.

To determine if static strain has an effect on the response variable, the largest strain range is desired. Maximum strain to be applied is set based on the maximum strain that can be applied to the specimen without failure. Using 6061-T6 properties from MIL-HDBK-5J [Department of Defense (2003)], the maximum allowable strain before specimen yield:

$$\varepsilon_{ty} = \frac{F_{ty}}{E} = \frac{35\text{ ksi}}{9900\text{ ksi}} = 3535\mu\varepsilon \tag{2}$$

As a precaution to prevent specimen yield, the maximum strain is set at 3000 $\mu\varepsilon$, and the number of static strain levels is set at 11: 0 to 3000 $\mu\varepsilon$, in 300 $\mu\varepsilon$ increments.

Since OC curves are based on a noncentral F distribution, numerator and denominator degrees of freedom must be determined for equation (1). Montgomery gives the DOF calculations as:

$$\nu_1 = b - 1 \tag{3}$$

$$\nu_2 = ab(n-1) \tag{4}$$

Using the parameters listed above and iterating sample size n gives the following values of β:

Table 3: Probability of Type II Error (β) Calculations Based on Changing Sample Size, n (11 strain levels, α = 0.05)

a	**b**	**D**	σ	**n**	Φ	ν_1	ν_2	β
2	11	10	5	2	0.8528	10	22	0.65
				3	1.044	10	44	0.525
				4	1.206	10	66	0.295
				5	1.348	10	88	0.195

Configuration of the data collection system limits sensor sample size to five per sample. Table 3 shows that with five sensors per glue type, the probability of committing a Type II error is an unacceptable 19.5%. It should be noted that with two or three sensors the probability of committing a Type II error is worse than 50-50.

Reducing the number of static strain levels from 11 to 9 (0 to 3000 $\mu\varepsilon$ in 375 $\mu\varepsilon$ increments) changes the numerator degrees of freedom from 10 to 8, giving the following values of β:

Table 4: Probability of Type II Error (β) Calculations Based on Changing Sample Size, n (9 strain levels, α = 0.05)

a	**b**	**D**	σ	**n**	Φ	ν_1	ν_2	β
2	9	10	5	2	0.9428	8	18	0.62
				3	1.154	8	36	0.475
				4	1.333	8	54	0.240
				5	1.496	8	72	0.090

Table 4 shows that 5 sensors per sample gives a 9% probability of committing a Type II error. This value is considered acceptable for the experiment.

4 Initial Results and Analysis

Five test specimens were fabricated and tested at zero strain to provide a true estimate for the response standard deviation, σ, for the test configuration. Figure 5 shows one test specimen with 5 PZT pitch-catch pairs of each glue type installed for testing.

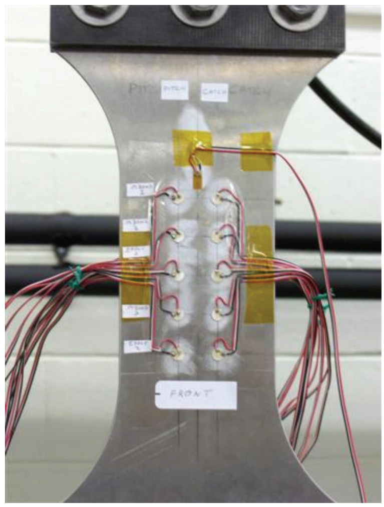
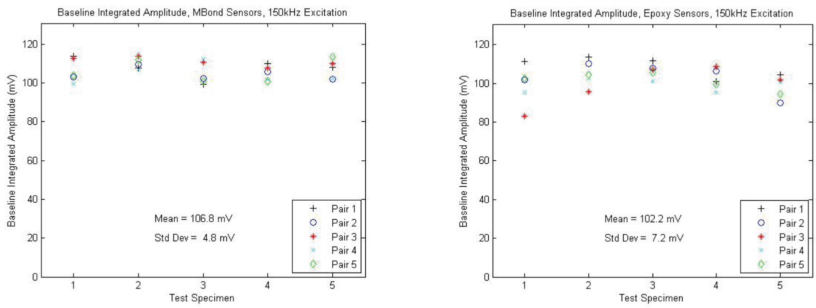


Figure 5: Ten pitch-catch PZT pairs per test specimen, 5 pairs on front, 5 pairs on back (not shown)

Figure 6 provides scatterplots of the baseline integrated amplitude for the 25 PZT pairs of each glue type broken out by specimen. Standard deviation of the responses approximates the 5mV assumption, with MBond pairs having a 4.8 mV σ, and Epoxy pairs having a 7.2 mV σ.

Differences between the MBond and Epoxy PZT pairs were seen in both average responses (107 vs. 102 mV) and standard deviation (4.8 vs. 7.2 mV). The difference in the average responses was found to be statistically significant using both the standard t-test assuming unequal variances (p-value = 0.0115) and the non-parametric Wilcoxon rank-sum test (p-value = 0.0257). Both the MBond and Epoxy 25 pitch-catch PZT pair samples passed the Shapiro-Wilk normality test. Based on these results, hypothesis S1: H_0 = Average baseline sensor response is equal for 2 glue types is rejected.

Figure 7 presents results of the static load testing. Figure 7(a) and 7(b) present the individual MBond and Epoxy pair results plotted against the strain level. Summary



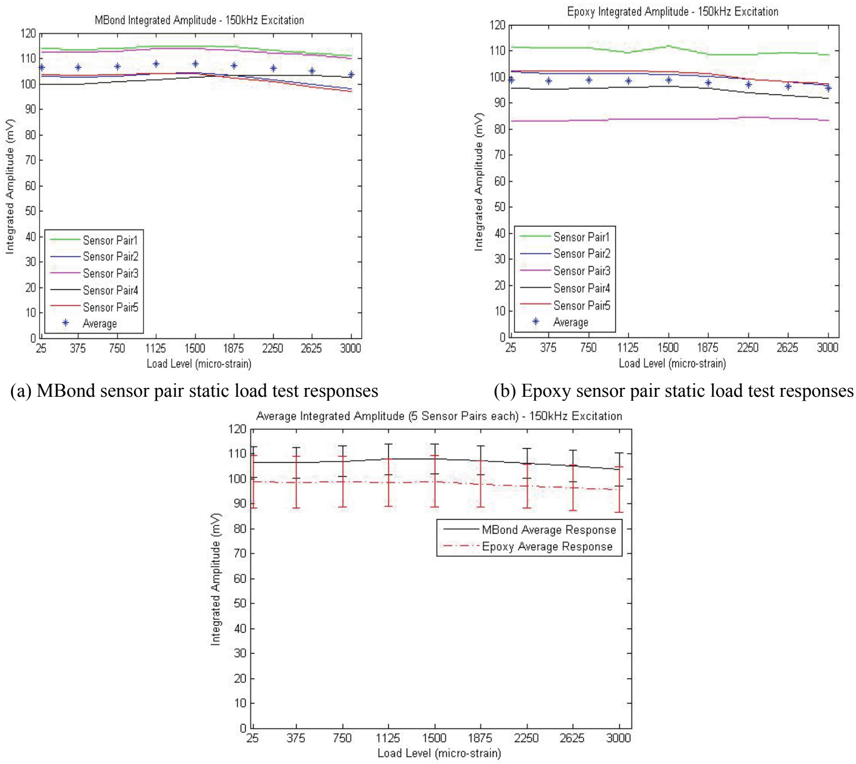
(a) Baseline responses from MBond PZT pairs (b) Baseline responses from Epoxy PZT pairs

Figure 6: Difference in mean baseline responses from MBond and Epoxy PZT pairs was statistically significant

Figure 7(c) presents the five pair averages for each glue type with corresponding error bars and standard deviation for each glue type plotted on a separate axis. General feature analysis of the curves shows consistent standard deviation for each glue type (∼6 mV for MBond pairs ∼10 mV for Epoxy pairs), and a small downward trend in average response starting at approximately the 1875 microstrain level. But these downward trends were found to be statistically insignificant using the two-tailed paired t-tests comparing the average responses after the 3000 microstrain load with the baseline responses at 25 microstrain. Based on these results, hypothesis S2: H_0 = Average baseline response does not change after applying a $3000\mu\varepsilon$ static strain is accepted.

5 Conclusion

This study presented a design of experiments (DOE) approach to develop a systematic method to determine the durability and performance of a PZT-based SHM sensor subjected to aircraft environmental factors. The consistent and predictable performance of SHM sensors after extended exposure to the aircraft environment is key to viable SHM systems. An initial round of testing showed statistical significance between the performance of identical sensors glued to test specimens with different glue types. Tests also showed no statistically significant change in sensor response after subjecting sensors to single cycle static strain loading up to $3000\mu\varepsilon$. Follow-on testing will determine the statistical significance of response changes due to cyclic strain.



(a) MBond sensor pair static load test responses

(b) Epoxy sensor pair static load test responses

(c) Summary responses for MBond and Epoxy PZT pairs

Figure 7: MBond and Epoxy pairs PZT pairs showed no statistical change

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