DURABILITY ASSESSMENT OF PZT-TRANSDUCERS FOR GUIDED WAVE BASED SHM SYSTEMS USING TENSILE STATIC AND FATIGUE TESTS

Christoph MEISNER[1], Christian STOLZ[1], Frank HOFMANN[2]
[1]Airbus Defence and Space, Manching, Germany
[2]Wehrwissenschaftliches Institut für Werk- und Betriebsstoffe (WIWeB), Erding, Germany
[1]christoph.meisner@airbus.com

Abstract. Structural Health Monitoring (SHM) systems are used within various industries for different application scenarios. Military aviation industry focuses on application scenarios to satisfy the future needs of autonomous health diagnostic and prognostic capabilities. Numerous investigations in the area of damage detection have shown that Guided Wave based SHM techniques offer a great potential to fulfil the diagnostic requirements for these systems. In service applications generate great demands concerning reliability and durability of system components which have to be considered for certification. Aerospace structures are exposed to harsh operational conditions (environmental and structural loading effects) affecting the diagnostic capabilities of individual system components as well as the performance of the diagnostics algorithms. These effects have to be considered for application of SHM systems enabling reliable damage detection performance.

Guided Wave based SHM techniques typically use lightweight PZT-Transducers which are permanently applied to the monitored component to assess its structural condition. This paper presents results of durability tests performed using co-bonded PZT-Transducers on composite panels under tensile static and fatigue loading. Different measurement techniques (e.g. measurement of electric charge vs. applied strain) are used to determine sensitive failure indicators of PZT-Transducers. Additionally, the effect of degrading PZT-Transducers on signal generation and Guided Wave sensing is evaluated to assess the diagnostic capabilities of this SHM method. These results are used to verify the applicability of PZT-Transducers for Guided Wave based SHM for aerospace structures considering operational loading conditions.

1. Introduction

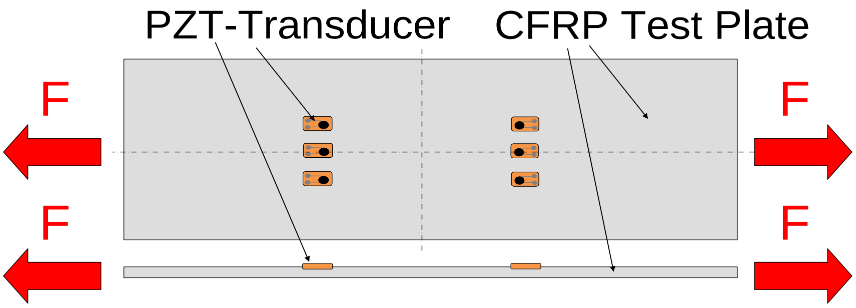
Structural Health Monitoring (SHM) Systems utilize permanently attached sensors, which allow a continuous monitoring of the structural component. Damages are directly tracked and maintenance intervals can be adjusted, enabling Condition Based Maintenance (CBM). Considering in-service applications, these SHM sensors are facing harsh operational conditions through the entire lifetime of the aircraft.

Guided Wave based SHM Systems utilize structurally attached PZT-Transducers (lead zirconate titanate) to excite Guided Waves. These waves propagate within the boundaries of a structural component over large distances [1]. Typically a pre-recorded reference signal without damage is compared with a measurement signal representing the current condition of the monitored component. The information of these signals is used to determine the structural condition of the component. This monitoring approach assumes that signal changes are evoked by damages. Other parameters affecting the wave propagation have to be compensated. Effects of environmental parameters like temperature [2,3] and humidity [4] and boundary effects like mechanical loading [5] are investigated in literature. Compensation techniques have been developed for laboratory applications [6,7], which have to be validated for real aircraft structures considering operational conditions.

The effect of PZT-Transducer degradation due to mechanical loading has been investigated by Gall et al. [8] and Moix-Bonet et al. [9]. First methods are defined to characterize the conditions of PZT-Transducers by monitoring the electro-mechanical impedance (EMI) [10]. In this work, the durability of PZT-Transducers has been investigated using tensile static and fatigue tests. The aim is to determine strain limits of co-bonded/embedded PZT-Transducers to enable reliable damage detection performance. Different measurement techniques are used to compare and identify sensitive failure indicators to detect PZT-Transducer degradation.

2. Experimental Setup

Carbon Fibre Reinforced Plastic (CFRP) plates with co-bonded (embedded) PZT-Transducers (Acellent$^{®}$ SMART Layer$^{®}$) are analysed using tensile tests to investigate the static and dynamic failure strain of PZT-Transducers at room temperature. Each coupon includes 6 PZT-Transducers positioned in 2 rows opposite to each other with 3 PZT-Transducers each (compare Pic. 1).



Pic. 1. CFRP Coupon for tensile test with integrated PZT-Transducers

During testing the coupons are hydraulically clamped in an universal testing machine “Instron Structural testing systems 8805”. An adhesively bonded strain gauge and a temperature sensor are used to monitor strain and temperature. To determine the degradation of the PZT-Transducers, two different measurement techniques are utilized: Measurement of electrical charge and measurement of the EMI including all its constituent parts. The electrical charge generated by the mechanical loaded PZT-Transducers is measured using the charge amplifiers KISTLER 5007 and 5011. EMI measurements are performed using the impedance analyser Cypher C60.

Guided Wave measurements are utilized to investigate the effect of degradation on the signal actuation and sensing properties of PZT-Transducers. For Guided Wave actuation and sensing, the measurement system Acellent® Scan Genie® II has been used. Different actuation frequencies are evaluated to identify signal changes within the wave packages containing the asymmetric (A0) and symmetric (S0) Lamb Wave modes.

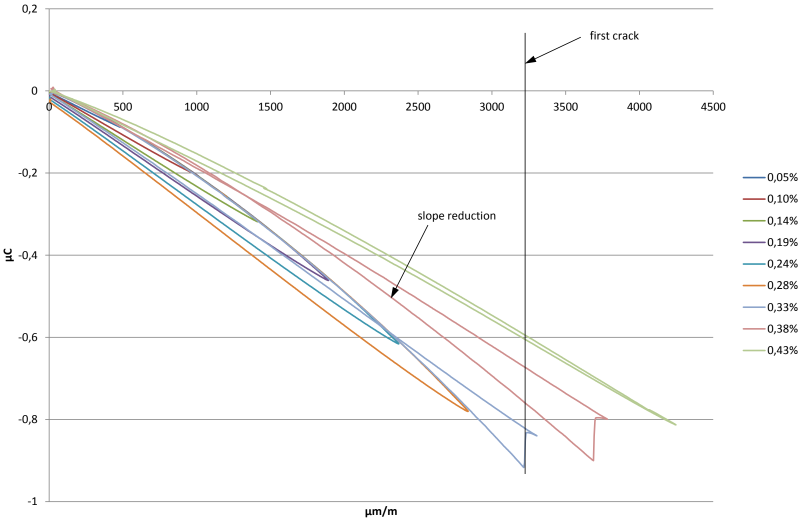
The test setup is divided into two subsequent parts: First, quasi-static tensile ramp loadings are performed to investigate the maximum tensile static strain of co-boned PZT-Transducers. Afterwards, different strain levels between 50% and 70% of the recorded max. tensile static strain have been selected for tensile fatigue testing. The fatigue loading is performed with constant amplitude and constant frequency sine wave. The ratio between minimum and maximum strain is set to R=0.1. To avoid rate dependency effects and temperature rise of the specimen, the cycling frequency is limited to 5 Hz.

For the quasi static tests, the EMI and Guided Wave measurements are performed before and after each loading step, while the electrical charge is measured continuously during the quasi-static ramp loading of the specimens. For the fatigue tests, cycling is stopped at predefined intervals and EMI and Guided Waves measurements are executed. During fatigue cycling, automated electrical charge measurements are used to identify precisely changes of the PZT-Transducer. Additionally, before and after each cycling block, quasi-static ramp loadings with electrical charge measurement have been performed.

3. Experimental Test Results

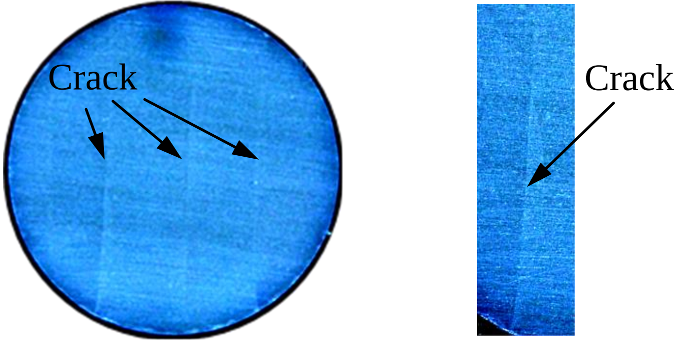
3.1 Static Tests

Pic. 2 shows the electrical charge curves measured in µC plotted against the tensile strain for different quasi-static ramp loadings. The curves show a slight nonlinear behaviour during loading followed by a linear decrease of charge during unloading. All charge measurements up to 2800 µm/m strain show a reproducible behaviour. The charge curve “0.33%” experiences a kink at approx. 3200 µm/m followed by a slope reduction for the subsequent loading steps. Gall et al. [8] describes this kink behaviour as a result of a cracking PZT-Transducer disk decreasing the overall strain within the disk leading to a reduced charge output.



Pic. 2. Electrical charge curves for tensile quasi-static loadings

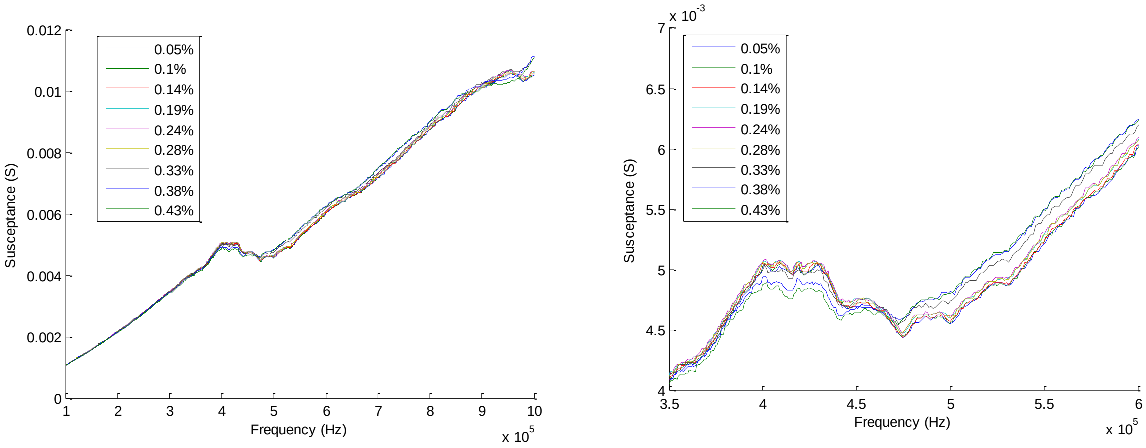
The PZT-Transducer cracking is confirmed by microscopic investigations of PZT-Transducer disks after mechanical loading (compare Pic. 3). The illustrated PZT-Transducer disk shows hairline cracks starting from the lower edge of the PZT-Transducer, growing in a straight direction perpendicular to the loading direction. Other failure mechanisms like debondings or electrical contact failures could not be recognized during microscopic investigation.



a) b)

Pic. 3. Microscopic picture of cracked PZT-Transducer disk after tensile quasi-static ramp loadings, a) complete PZT-Transducer disk with three cracks, b) enlarged area of left crack

The EMI measurements are evaluated with special focus on the susceptance spectrum as imaginary part of the admittance. In the lower frequency range (up to 300 kHz) the susceptance curves experience small changes (compare Pic. 4 a)). The highest sensitivity to detect PZT-Transducer degradation using EMI measurements can be found in the resonance area between 350 and 600 kHz (compare Pic 4 b) and [10]). The cracking of the PZT-Transducer disk at approx. 3200 µm/m evokes changes in the resonance area within the susceptance curves. The next loading steps followed by further degradation of the PZT-Transducer lead to a further changes within the resonance area.

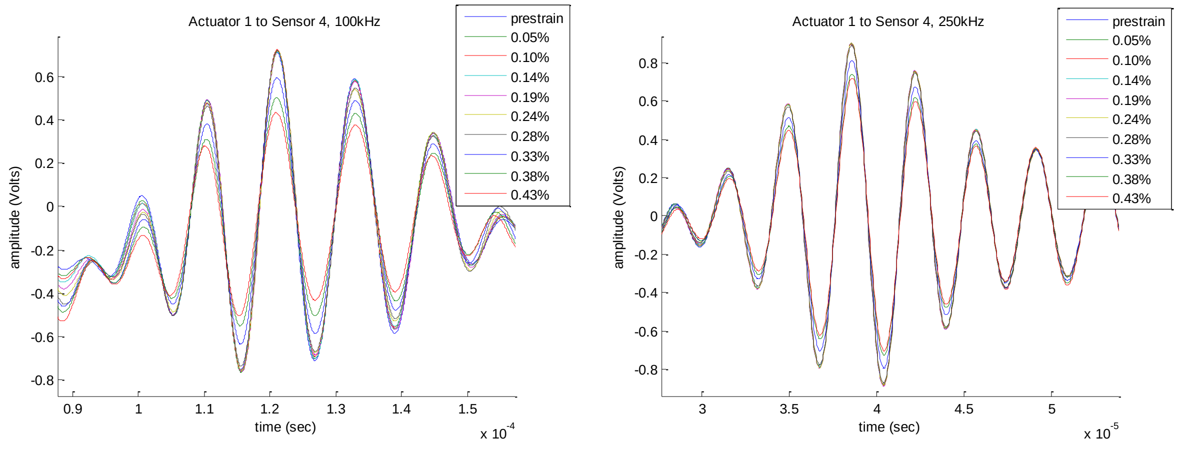


a) b)

Pic. 4. EMI measurements after different tensile quasi-static loadings, a) overview measurement range, b) enlarged resonance area

To check the effect of PZT-Transducer degradation on Guided Wave actuation and sensing, Lamb Waves are actuated in a pitch-catch network configuration. Different frequencies are investigated to determine the effect on the A0 and S0 Lamb Wave modes.

Both modes are directly affected by PZT-Transducer degradation (compare Pic. 5). Guided Wave measurement “0.33%” with cracked PZT-Transducer disk indicated by the electrical charge curves, shows an amplitude reduction for both modes. Further degradation of the PZT-Transducer due to higher loading levels evokes further amplitude reduction. A temporal shift or mode transformation cannot be recognized for the A0 nor for the S0 Lamb Wave mode.



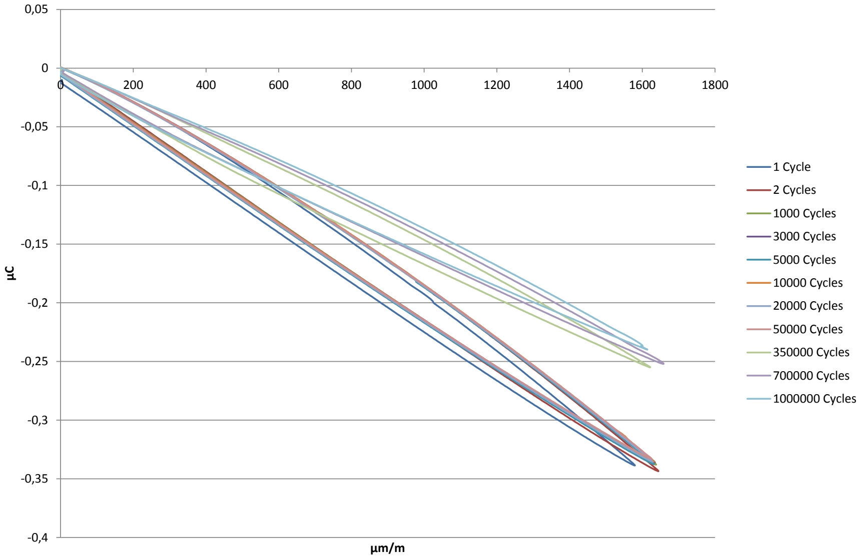
a) b)

Pic. 5. Guided Wave measurements after different tensile quasi-static ramp loadings, a) A0-Mode at 100 kHz, b) S0-Mode at 250 kHz

The quasi-static tensile tests have shown a cracking based degradation mechanism for co-bonded PZT-Transducers. The PZT-Transducers start degrading at a mechanical strain level between 2350 µm/m and 3220 µm/m. The degradation mechanism leads to a direct effect on the Guided Wave actuation and sensing. The PZT-Transducers remain generally functioning, but PZT-Transducer degradation will presumably affect the damage detection performance of the SHM System. An identification method to detect PZT-Transducer degradation based on EMI measurements seems to be a promising approach.

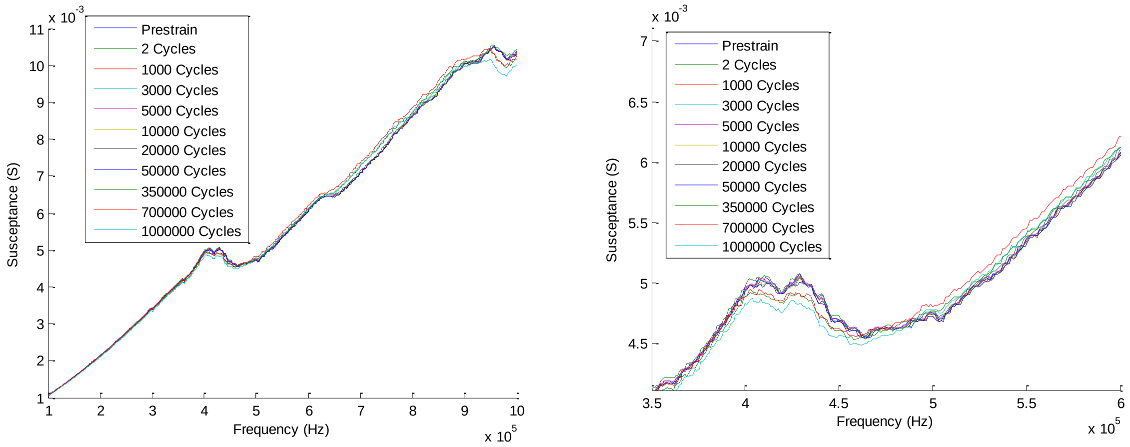
3.2 Fatigue Tests

The tensile fatigue tests have been performed applying several cycling blocks. Pic. 6 shows electric charge measurements for quasi-static ramp loadings after different cycling blocks. For the illustrated picture the cycling blocks are performed with a max. strain of 1650 µm/m. The electric charge curve measured after 350,000 cycles shows a significant slope reduction indicating PZT-Transducer failure between 50,000 and 350,000 cycles. Evaluating the automated electrical charge measurements performed during fatigue cycling reveals initiating PZT-Transducer degradation starting at 331,100 cycles.



Pic. 6. Electrical charge curves for tensile quasi-static ramp loadings after different fatigue loading blocks (max. tensile strain 1650 µm/m)

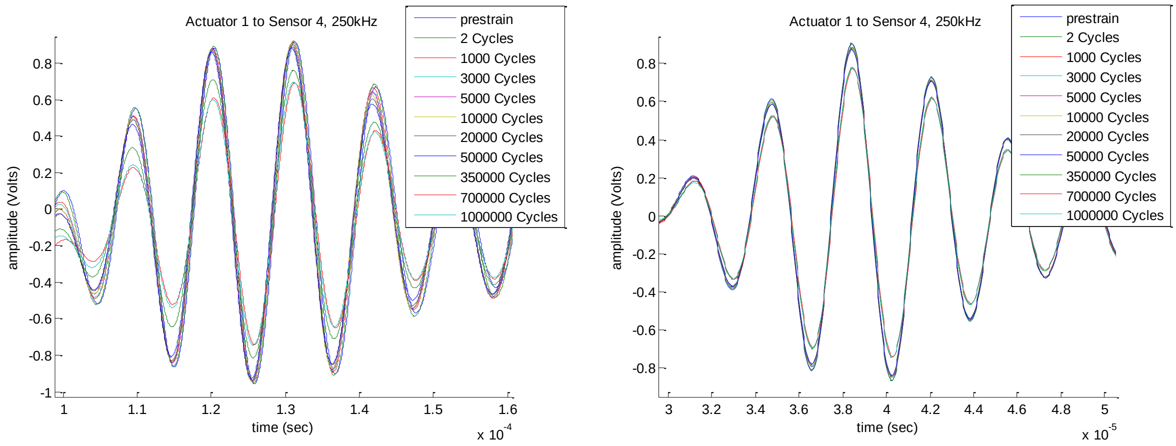
The susceptance curves for the fatigue loaded PZT-Transducers show similar behaviour compared to the static tests. While the measurement range up to 350 kHz is only slightly affected (Pic. 7a)), the resonance area between 350 and 600 kHz shows changing measurement values after 350,000 cycles and 1,000,000 cycles indicating progressing PZT-Transducer degradation (Pic. 7b)).



a) b)

Pic. 7. EMI measurements after different tensile fatigue loading blocks (max. tensile strain 1650 µm/m) a) overview measurement range, b) enlarged resonance area

Pic. 8 shows Lamb Wave signals measured after different cycling blocks. Different frequencies are actuated to evaluate the effect of PZT-Transducer degradation on the A0 and S0 Lamb Wave modes. Similar to the quasi-static tests, the degradation of PZT-Transducer due to tensile fatigue loading, evokes amplitude reduction of the received Lamb Wave signals. This effect can be observed for both wave modes. The first amplitude reduction occurs after 350,000 cycles. This directly correlates to the electrical charge and EMI measurements. The A0 Mode shows generally a higher amplitude reduction compared to the S0 Mode. A temporal shift or mode transformation of the wave package due to PZT-Transducer degradation cannot be recognized.



a) b)

Pic. 8. Guided Wave measurements after different tensile fatigue loading blocks (max. tensile strain 1650 µm/m), a) A0-Mode at 100 kHz, b) S0-Mode at 250 kHz

Tensile quasi-static and fatigue tests have shown an identical PZT-Transducer degradation mechanism. The initiated degradation, identified by electrical charge measurements, has been confirmed by a changing susceptance spectrum and amplitude reduction of the received Lamb Wave signals. Similar effects have been observed for all tested tensile fatigue loading levels. Identical to the quasi-static tests, the PZT-Transducer remains generally functioning, but with effects on the Guided Wave actuation and sensing presumably affecting the damage detection performance of the SHM System. Again, the EMI method seems to be a promising method to detect initiating and progressing PZT-Transducer degradation.

4. Summary

With tensile static and fatigue tests the strain limits of co-bonded/embedded PZT-Transducers within CFRP plates have been investigated. Electrical charge measurements of tensile loaded PZT-Transducers have been used to identify initiating degradation of PZT-Transducers. The electro-mechanical impedance, especially the imaginary part of the admittance, the susceptance, has shown a good sensitivity to detect degradation of PZT-Transducers. To determine the effect of PZT-Transducer degradation on the overall SHM System performance, Lamb Waves have been actuated in a pitch-catch network configuration for different degradation states of the PZT-Transducers. The results have shown that both A0 and S0 Lamb Wave modes experience amplitude reduction with increasing PZT-Transducer degradation. This effect has been identified for tensile quasi-static and fatigue tests. A temporal shift or mode transformation of the propagating wave packages has not been detected.

For SHM applications in aircraft using PZT-Transducers, a reliable and automated method is necessary, which is able to determine the health status of all PZT-Transducers before performing damage detection measurements. The results of this study showed that the measurement of the electro-mechanical impedance, with special focus on the susceptance spectrum, is a promising method to be used within aircraft environment.

5. References

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