Check of Piezoelectric Transducers Using the Electro-Mechanical Impedance

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ABSTRACT

The use of piezoelectric wafer active sensors in structural health monitoring systems implies the necessity to check these components for their functionality, especially when the sensors are embedded in the structure. This paper introduces two novel approaches based on electro-mechanical impedance measurements and compares them with a traditional approach based on the slope of the susceptance spectrum. The change of the resistance spectrum as well as the change of the correlation of susceptance spectra is established as damage indicator. In an experimental setup the mechanical durability of a piezoelectric patch transducer, directly embedded in the structure, was tested. It has been shown that this application of load causes partial sensor breakage, which, for this particular type of PWAS, can hardly be detected with the help of the susceptance slope. The good feasibility especially of the proposed damage indicator, based on correlation within the susceptance spectrum, is demonstrated.

KEYWORDS : *SHM, Sensor Faults, EMI, Integrated Transducers, Signal Processing*

INTRODUCTION

One popular sensor type for active monitoring technologies in structural health monitoring (SHM) is the piezoelectric wafer active sensor (PWAS), due to its multipurpose application as actuator and sensor and its low cost. It is used to generate a wave field, which interacts with the structure and is recorded by a set of other PWASs. Generally the use of sensors requires that those are functioning correctly, especially when long term monitoring is performed. Within the EU-project SARISTU one key issue is to integrate the sensors during the manufacturing process to shorten the process of mounting an SHM system, which includes the fact that the sensor system will be installed in a new aircraft, enlarging the necessary life time of the monitoring system. This emphasizes the need to periodically check the piezoelectric transducers during their entire lifetime.

Early works on this topic are published by Friswell and Inman [1]. Their approach needs a structural model for a comparison with measurements. This is not the case for works on sensor fault detection due to the observation of the admittance, carried out by Park et al. [2]. The susceptance as imaginary part of the reciprocal of the electro-mechanical impedance (EMI) includes the capacitance of the piezoelectric element. Thereafter, a breakage of the element will decrease the capacitance leading to a decrease of the susceptance slope, while a debonding of the sensor from the structure will cause the contrary effect. Using the same physical quantity, for circular PWAS Buethe et al. [3] propose the use of a physical model of the implemented PWAS and its adaptation to measurements to obtain information about the state of the PWAS. Unfortunately this requires a lot of knowledge about the applied PWAS, e.g. its material properties. As e.g. temperature has a huge influence on the susceptance [3, 4], Park et al. suggest the comparison of the susceptance slope within a batch of sensors to avoid the necessity of taking a huge amount of data as baseline in a range of environmental and operational conditions (EOCs) [5].

In this work, the authors have tested a patch transducer from DuraAct^{TM}, deployed in the SARISTU project, co-bonded to CFRP band-shaped samples. A strain-cycle life diagram for a similar patch transducer glued onto a CFRP sample (secondary bonding), has been described by Gall et al. [6]. They have been using a similar cyclic loading setup and deploy the charge, produced by the sample bending, as damage indicator, which is hardly employable for realistic application scenarios. Here, the existing method of monitoring the slope of the susceptance, as well as two novel approaches using signal processing methods are applied to the physical quantity EMI, to check the PWAS in regular intervals during four-point bending tests, in which the PWAS is subjected to tension. The new approaches are described in the section "Methods", followed by the chapter "Experimental Setup". Afterwards the suggested methods and a comparative approach are applied on the gathered data. The good feasibility of the newly developed damage indicators is shown in the section "Results". Here also suggestions for an effective application of the EMI based methods are given. Finally a conclusion is drawn.

1 METHODS

To detect sensor faults, measurements of the electro-mechanical impedance and its accompanying quantities, like the admittance as its reciprocal, the susceptance as imaginary part of the admittance and the reactance as real part of the impedance are used. A characteristic frequency spectrum of resistance and susceptance for a comparable Acellent SMART layer PZT, with $\emptyset = 6.35\,mm$ attached to a CFRP plate is shown in Figure 1.

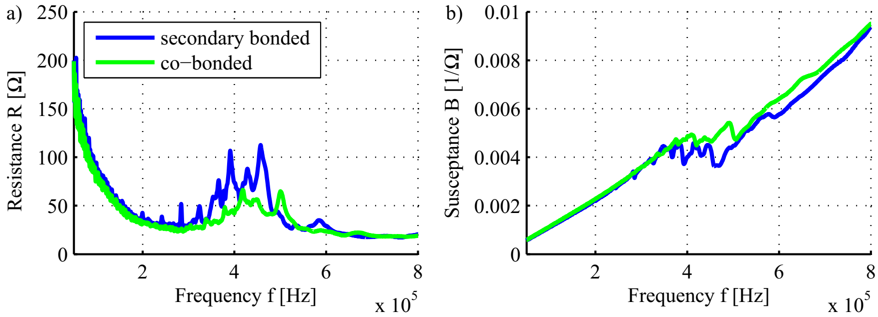

Figure 1: Resistance (a) and susceptance (b) for a secondary bonded and a co-bonded PWAS attached to a CFRP plate

Different ways of bonding the PWAS to the structure, like co-bonding or secondary bonding, result in slightly different spectrum characteristic. Different damages have been proven to do so in a similar way [2, 3]. As the electro-mechanical impedance and its related quantities are known to be temperature sensitive, in the following we assume constant conditions or the availability of baseline measurements at a temperature range for ease of temperature compensation. While the resistance R is generally decreasing with increasing frequency a local maximum in a frequency range of 250 to 600 kHz is visible. Within the same frequency range the increasing susceptance B shows a resonance behavior interrupting the linear slope.

As a parameter, which is changing when damage occurs, the area A_R under the resistance in the frequency range mentioned afore, is suggested. It is calculated as follows:

$$A_R = \int_{250\,kHz}^{640\,kHz} R(f)df \tag{1}$$

This damage indicator needs to be calculated for a single PWAS in undamaged condition to provide a baseline. For a PWAS check A_R is evaluated and compared to the baseline. A decreased value indicates damage.

The second and third damage-indicating parameter, suggested in this contribution, also focus on the specific frequency range but use the susceptance spectrum. To compare the susceptance spectra of two measurements, the correlation coefficient is calculated. The correlation coefficient is applied as damage indicator for structural damage in various publications (e.g. [7, 8]). Its use will be introduced in two different ways here. Either a measurement is compared with a baseline measurement of the same sample leading to the calculation of a damage index DI_{CC} or it is compared to a batch of samples of the same type under similar EOCs and a damage index DI_{CCb} is calculated. While DI_{CC} is thought to be very effective, if a baseline measurement under identical EOCs exists, the second approach is also applicable for first checks after installation of a system, provided that only a small amount of the whole batch is defect. With this method also the difficulty of changing environmental conditions is eased, as all used data is taken at the same time, most likely under similar EOCs. Both have in common the use of a relatively high frequency spectrum, which is usually above the frequencies used for AU. If $B_1(f)$ is a baseline susceptance spectrum and $B_2(f)$ is a new measurement, its covariance matrix can be calculated as $\boldsymbol{C}$. From this the damage index DI_{CC} is calculated according to (2), were the expression subtracted from one is the correlation coefficient CC.

$$DI_{CC} = 1 - \frac{C_{12}}{\sqrt{C_{11}C_{22}}} \tag{2}$$

Provided $\boldsymbol{B}$ is a matrix containing all susceptance measurements of a batch of m identical PWAS at a certain measurement date, with B_n being the susceptance spectrum of the nth PWAS. Then the damage index DI^n_{CCb} for PWAS n is calculated according to (3) as subtraction of the mean of all correlation coefficients without comparing nth measurement and the mean of all correlation coefficients calculated with the nth measurement (see (3-6)). Here $\boldsymbol{C}$ is of size mxm.

$$DI^n_{CCb} = |CC_{\notin n} - CC_{\in n}| \tag{3}$$

$$CC_{\notin n} = \frac{1}{(m-1)^2 - m + 1}\sum CC_{ij} \quad \text{with } i,j \in \{1, \dots, m\}/\{n\} \;\; i \neq j \tag{4}$$

$$CC_{\in n} = \frac{1}{(m-1)}\sum CC_{ni} \quad \text{with } i \in \{1, \dots, m\}/\{n\} \tag{5}$$

$$CC_{ij} = \frac{C_{ij}}{\sqrt{C_{ii}C_{jj}}} \tag{6}$$

As $CC_{\in n}$ and $CC_{\notin n}$ are in the interval of $[0, \dots, 1]$ the damage index DD^n_{CCb} has the same range. Zero implies no damage, while increased index indicates increased damage size.

According to Park et al. [2] the slope of the susceptance can be taken as an indication of sensor damage. It is calculated as a traditional method of PWAS check and will be compared with the results of aforementioned methods. A frequency spectrum from 10 kHz to 250 kHz was chosen, to calculate the slope coefficient SC from a linear regression of the susceptance curves.

2 EXPERIMENTAL SETUP

As specimens, innovative patch transducers Type DuraAct™, co-bonded on 4-point bending multilayer CFRP-band samples have been used. They are composed of a PZT disc, embedded in a ductile polymer along with the required electrodes, electrical contacts and insulators [9]. Their design, geometric and material properties can be seen in Figure 2. The patches have been co-bonded to CFRP samples. In the manufacturing process the patch is positioned on the uncured CFRP-band and adhered during the curing process in the autoclave.

To introduce damage to the PWAS the specimens were tested

(1) in quasi-static and stepwise quasi-static tests until failure,
(2) under cyclic loading and
(3) in stepwise quasi-static tests.

The quasi-static tests were conducted to find out the critical strain values for tension and compression. To check the transducers the EMI spectrum was collected before and after each loading step. Resistance and susceptance spectra are evaluated from these measurements. A detailed description of the setup and its results can be found in [10] and results are discussed here only briefly. The cyclic tests have been performed at 4 levels equally distributed between 35% and 70% of this maximum level of tensile strain. The cyclic tests have been paused at fixed intervals to record the EMI spectrum in unloaded condition. In the stepwise quasi-static tests the EMI spectrum is also measured at different strain levels in loaded condition without and with PWAS damage. For both the spectra of resistance and susceptance is evaluated.

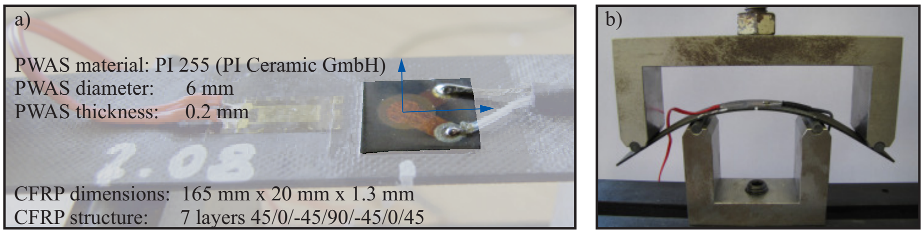

Figure 2: a) Properties of samples with DuraAct^{TM} patch transducers, b) Experimental setup – Case (3)

3 RESULTS

3.1 Critical Strain Value

In the static tests as a critical tensile strain value from six samples a mean of 0.58% with a standard deviation of 0.0228 was determined. The point of damage is audible and moreover visible as one or multiple cracks under the microscope. Micrographs of one sample, which was loaded stepwise in a quasi-static test, are shown in Figure 3.

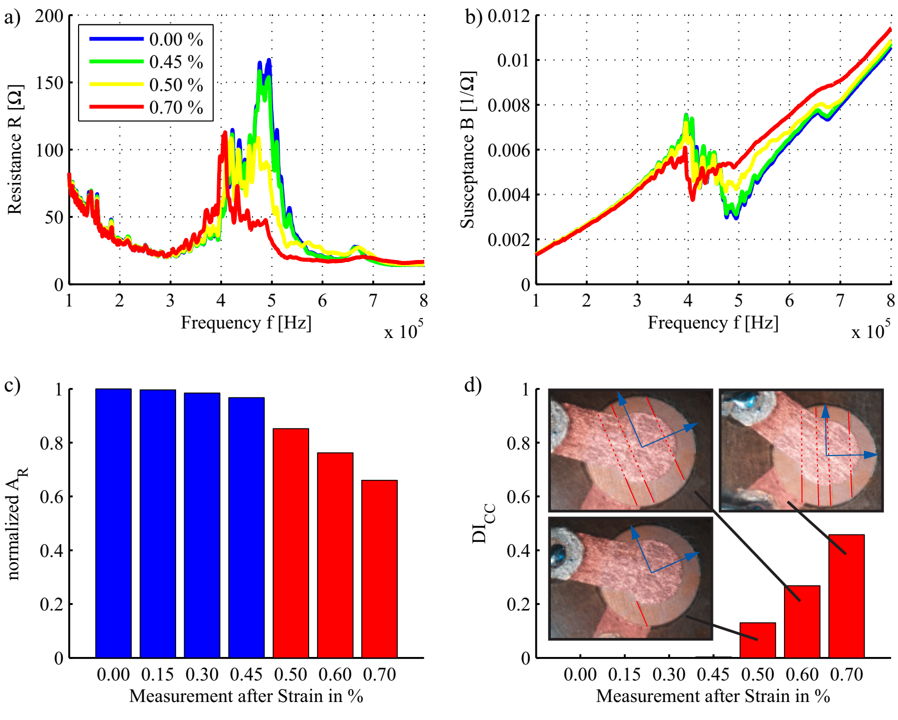

Figure 3: Exemplary resistance (a) and susceptance (b) spectra for the DuraAct^{TM} patches in undamaged and damaged condition (legend gives the actual strain in %) and evaluation of damage specific parameters A_R (c) and DI_{CC} (d), including damage visualisation with micrographs after loading until given levels of strain (d)

No limit could be found for the compression and the experiments were stopped at 1% compression strain. Exemplary resistance and susceptance curves after loading until given strain levels and subsequent unloading, as well as the evaluation of the suggested damage indicators A_R and DI_{CC} are shown in Figure 3. Both indicate the damage and show larger changes with increasing extent of the damage.

3.2 Comparison of Damage Indicators A_R, DI_{CC} and SC for Dynamic Testing

For the cyclic test, levels of 35 %, 47 %, 58 % and 70 % of the critical strain value of 5800 $\mu m/m$ were used. The experimental results have been employed for the calculation of the damage-indicating parameters A_R, DI_{CC} and SC described in the "Methods" section.

The evaluation of the slope of the susceptance SC for all tested samples is shown in Figure 4. It can be seen, that this parameter is almost constant for most samples. A slight increase can be found for a few samples S at 47 % and 58 % strain level, while for one sample at 70 % strain level a major decrease can be detected.

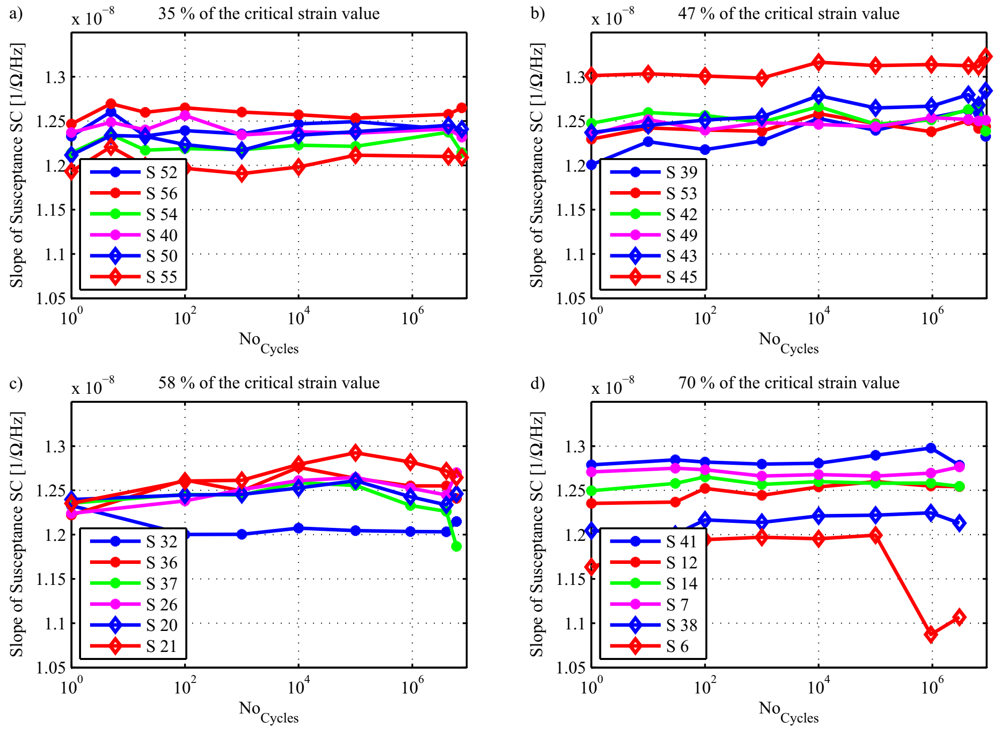

Figure 4: Evaluation of the slope coefficient SC at four levels of strain: a) 35 % b) 47 %, c) 58 % d) 70 % of 5800 µm/m critical strain value, with 6 samples each

The evaluation of the normalized area under the resistance spectrum within a frequency range of 250 to 640 kHz A_R for all tested samples is shown in Figure 5. While for the first strain level (a)) all curves stay approximately constant, except two outliers, for 47 % (b)) already two samples show a decrease of A_R. For 70 % (d)) almost all curves decrease continuously with increasing number of cycles.

The evaluation of the first susceptance based damage indicator DI_{CC} for all tested samples is shown in Figure 6. While for 35 % (a)) no change of DI_{CC} is visible, for 47 % (b)) at 10000 cycles already one sample reveals in increased index. At highest number of cycles, two samples show an increased damage index. For 70 % all samples exhibit high damage indices, which are increasing with number of cycles. One sample, which index starts to increase first, shows a saturation effect from 10^5 cycles (d)).

After the fatigue tests, the specimens have been investigated by means of micrographs in order to determine the transducer failure mode. For all failed samples, the piezoceramic disk contained visible cracks, while in the 100 % of the undamaged specimens no cracks or any other defects where observable on the PZT disk.

Both damage indicators A_R and DI_{CC} show the damage and its proceeding quite well. The general behaviour with increasing number of cycles and damage size shows higher monotony and regularity for assigned DI_{CC}. Nevertheless after a critical damage size, no further increase of damage index is detectable. The damage type 'crack' for the PWAS patch, used in these experiments is not detectable by monitoring the susceptance slope SC.

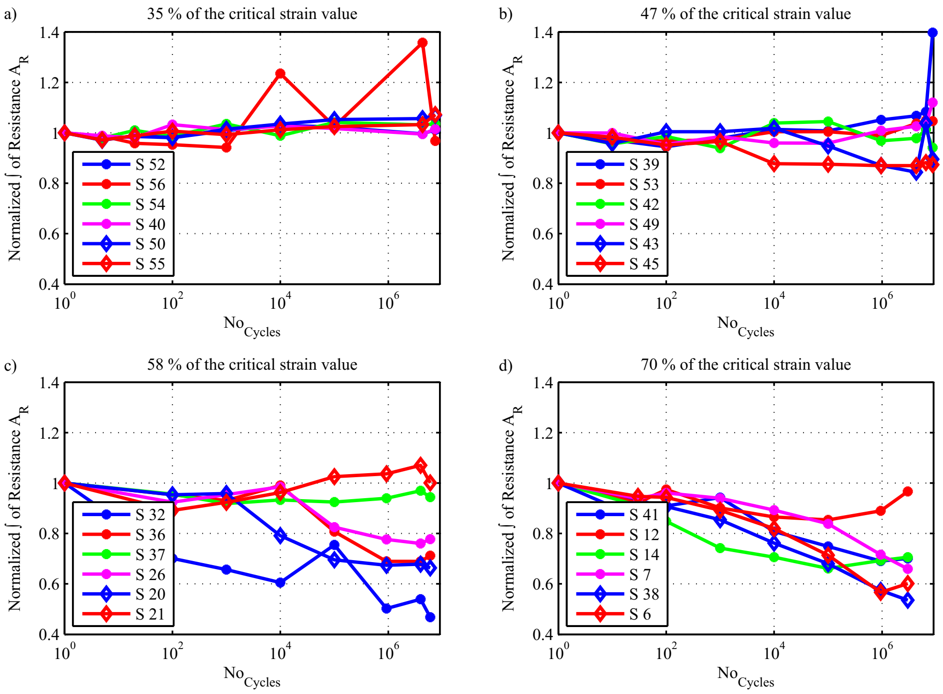

Figure 5: Evaluation of A_R at four levels of strain, a) 35 % b) 47 %, c) 58 % d) 70 % of 5800 µm/m critical strain value, with 6 samples each

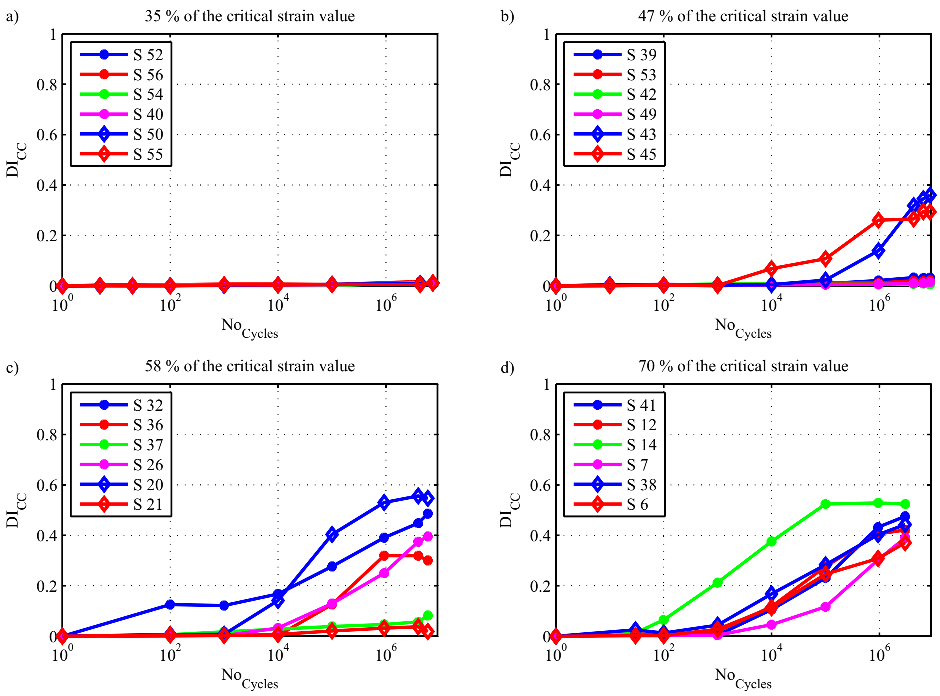

Figure 6: Evaluation of DI_{CC} at four levels of strain, a) 35 % b) 47 %, c) 58 % d) 70 % of 5800 µm/m critical strain value, with 6 samples

3.3 Use of Damage Indicator under Pre-Strained Condition

In real word applications, this kind of transducers will be attached to structures like aircraft wings or fuselage. For those cases normally a design limit of less than 0.1 % strain is given. Therefore it can be assumed, that this novel type of PWAS will withstand the application requirements. Nevertheless, a functionality test should be mandatory. Current state of the art suggests a testing of the PWAS functionality at zero strain. The tests conducted here, showed that only tensile strain could harm the PWAS, leading to a partial breakage. The third set of experiments was conducted to use the damage indicator DI_{CC} with measurements taken while the sample was pre-strained. Under bending load the general slope of the susceptance decreases like displayed in Figure 7 a). This is similar to its behavior under decreasing temperature (see [3]). As the damage index is based on correlation still a high correlation is given, resulting in a low damage indicator, although the slopes of the curves do not match very well (Figure 7 b)).

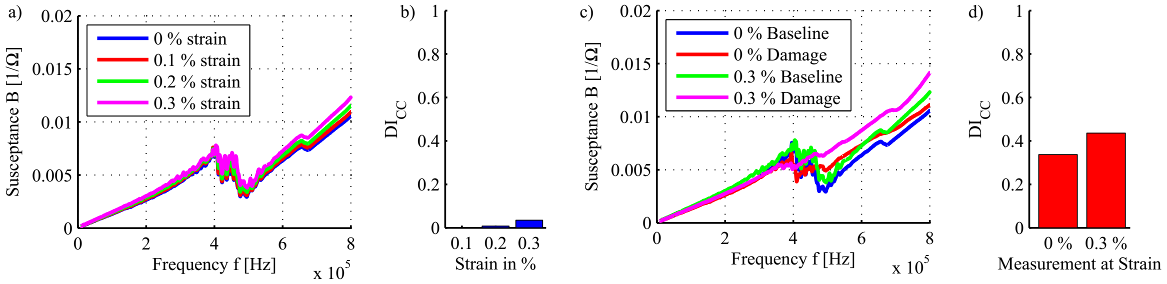

Figure 7: a) Susceptance spectra of one sample measured under strain and b) corresponding damage indicator DI_{CC}; c) Susceptance spectra at different pre-strain conditions, d) damage indicator evaluated from measurements with and without pre-strain

If a baseline measurement is taken at a defined level of strain, a calculation of DI_{CC} with new measurements at this strain level can be realized. An example of application is the pre-strain due to component weight under gravity. As it can be seen in Figure 7 d) this pre-loading increases sensitivity of the damage indicator proposed. The same damage condition was tested without and with preload. While for 0% pre-strain the damage indicator is 0.34, it is 0.44 for the preloading condition with 0.3% tensile strain. From these results the authors give the recommendation to test the PWAS functionality under tension, especially if the damage type, which was reproduced here, should be tested.

3.4 Evaluation of the Damage Indicator DI_{CCb} for "baseline-free" Checks

The third damage indicator DI_{CCb}, which is suggested under "Methods" is especially important for tests, where no baseline is available, e.g. a first check after installation.

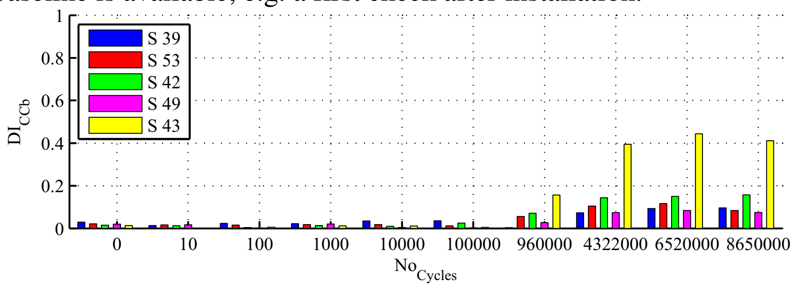

Figure 8: Evaluation of DI_{CCb} for four healthy (S39, S53, S42, S49) and one damaged (S43) patch transducers

This application is shown using the measurement data with a loading of 47% of the critical strain value including four undamaged and one damaged sample to make sure, that the vast majority of sensors are undamaged. Although DI_{CCb} of all sensors slightly increase at increasing cycle number, it is clearly visible, that DI_{CCb} of one sample (S43) shows a major increase (see Figure 8). From this, damage of the sample transducer S 43 can be assumed. This has also been confirmed by micrographs.

CONCLUSION

Promising damage indicators for the check of piezoelectric wafer active sensors have been introduced. The best performance, tested with co-bonded patch transducers, was given by DI_{CC}, a damage indicator, which is based on the correlation coefficient for susceptance spectra of the transducer. The produced damage of partial breakage could not be detected by monitoring the slope of the susceptance spectrum.

For the application of this method the authors suggest to take the electro-mechanical impedance measurements while the transducer is subject to pre-strain, as this improves the sensitivity of the investigated damage indicator. While for periodical checks a comparison between a baseline and current measurement of the same transducer under similar environmental and operational conditions gives good results, this procedure is not possible for first checks. Therefore the use of a comparison based on the correlation coefficients within a batch of transducers is suggested. The efficiency of this damage indicator DI_{CCb} has been shown.

All damage indicators have been tested only for this particular kind of damage with this patch transducer. For further research it would be important to test different transducers, showing other damage types. Especially for the statistical analysis the investigation on large distributed PWAS-networks with various cable lengths would be a challenge.

ACKNOWLEDGEMENTS

The research leading to these results has gratefully received funding from the European Union Seventh Framework Programme (FP7/2007- 2013) under Grant Agreement n° 284562.

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