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ADVANCED MEASUREMENTS IN STAR SPACE PROJECT ON STRUCTURAL HEALTH MONITORING

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Abstract – Accurate specimens representing aluminum spacecraft structures with piezoelectric wafer active sensor (PWAS) bonded on them were subjected to extreme temperature variations and radiations. The structure itself is affected by mechanical damages caused by fatigue and aging. The signature of structure's health is the real part of electromechanical impedance spectroscopy (EMIS) curves of a PWAS bonded on structure. Based on these EMIS records, damage metrics were calculated as root mean square deviation from healthy to damaged specimen. This paper presents a concise description of four investigative measurements, carried out with advanced electronic, optical and acoustic means.

Keywords: piezoelectric wafer active sensors, electro-mechanical impedance spectroscopy, scanning laser Doppler vibrometer, digital and scanning acoustic microscope

1. INTRODUCTION

This paper is based on a database consisting on a large amount of experimental data obtained in several research projects such as the STAR project code ID 188/2012, supported by National Authority for Scientific Research (ANCS), UEFISCSU [1], [2], [3]. The experimental part of the project addresses a problem specific to space applications, namely the effect of the extreme temperature variations and space radiations on the electromechanical impedance spectroscopy (EMIS) of the piezoceramic wafer active sensor (PWAS). Some aspects of these tests are given in Section 2.

2. TESTS, MEASUREMENTS, DATA PROCESSING

A considerable amount of testing stages, EMIS records, data processing and analytical assessments on damage identification, in order to qualify PWAS (piezoelectric wafer active sensors) transducers, and, more generally, Structural Health Monitoring (SHM) methodology, for use in space operations were performed in INCAS "Elie Carafoli" (www.incas.ro) and IFIN-HH (www.nipne.ro) labs in the years 2013, 2014. The records refer to either PWASs or specimens with bonded PWAS, without and with simulated defects. The PWAS transducer is also known as PZT (lead zirconate titanate). PWAS purchased from the company STEMINC (http://www.steminc.com/) were glued with M-Bond 610 Vishay epoxy adhesive [4] on the aluminum circular plate of 100 mm diameter and 0.2 mm thick. Mechanical damages were simulated as laser fabricated narrow through-the-thickness slit cuts (Fig. 1).

The space vehicles and satellites must perform current activities in a hostile environment. The main stress agents are cosmic rays (CRs), exposing at cryogenic or high temperature variations, high vacuum pressure. The temperatures in the near-Earth zones range between 120 °C for surfaces exposed to the Sun, and –183 °C in the case of unexposed surfaces.

(a) (b) (c)

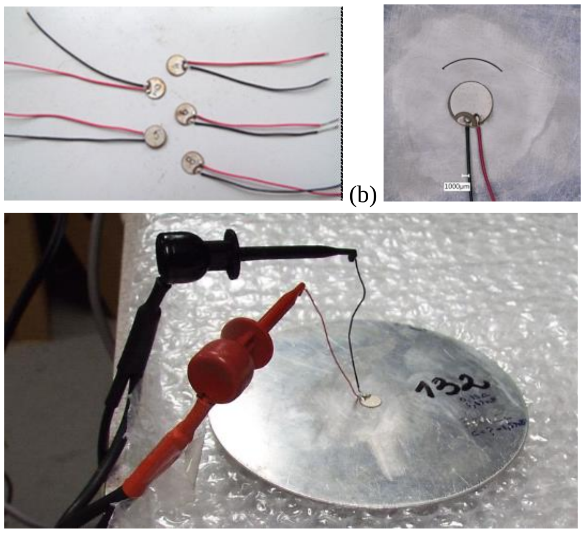


Fig. 1. (a) STEMINC PWASs # 4, 5, 6, 8, 9, (b) aluminum specimen #76 with arc type laser cut at 7 mm and central bonded PWAS and (c) circular specimens #132 without simulated mechanical damage, connected to the impedance analyser HP 4194

The experiments were conducted in a Gamma irradiation Chamber 5000, which contains a set of 60-Co circular distributed sources. The measured radiation flow value was 4.7 kGy/h.

The irradiation doses were calculated using the following data: (a) full dose estimated for a mission to Mars is 110 mGy/year average, which means a dose rate of about 15 μGy/h; (b) the largest absorbed doses determined by Pioneer 10 and 11 space probes were 15 kGy and 4.3 kGy, respectively. Therefore, the dose rate determined by Gamma irradiation Chamber 5000 was considered to be representative. The absorbed dose was set at full 23.5 kGy, corresponding to 5 hours of exposure at 4.7 kGy/h.

The outer space vacuum can reach 10^{-14} Pa. Vacuum pressures lower than 10^{-1} Pa were achieved by using Tritium Manifold, a high vacuum plant, containing a vacuum pump type TSH-171E Pfeiffer, and pressure vacuum controllers type TPG 262 Pfeiffer.

The program of the tests was carried out along five successive test cycles that have finally accumulated the precalculated 23.5 kGy integral irradiation dose, 2 hours at 196 °C and 2 hours at 100 °C, with a vacuum pressure of 10^{-2} –10^{-4} mbar.

A first system used to monitor structural health is the so-called EMIS signature, i.e. the spectrum of the electro-mechanical impedance $Z(\omega)$ of a PWAS transducer, free or bonded to structure measured by the *HP 4194* **impedance analyser.** The real part of impedance, Re ($Z(\omega)$), is very sensitive to the smallest variations in the high-frequency structural dynamics at local scales (of microns order), which are associated with the presence of incipient damage.

In short, the essence of the EMIS signature method consists in:

1) the fact that the PWAS is a high-frequency modal sensor;

2) the change in the EMIS signature is attributed to the change in integrity of the structure due to damage;

3) this change is exhibited only in Re ($Z(\omega)$), which follows with fidelity the resonance behavior of the structure vibrating under the PWAS excitation.

The signatures of the free PWAS and of the PWAS bonded to the aluminum disc specimens were measured. EMIS signatures were raised, as appropriate, on line (i.e. during the submission of proof at harsh conditions), or offline (after submission, i.e. at room temperature and without radiation), as in Figure 2. The impedance analyser connected to a free PWAS or a bonded PZT applies a continuous electrical signal. The amplitude ratio between the voltage and the current as well as the phase shift between them is measured obtaining the impedance at a given frequency. By comparing the EMIS signature at different times during the life time of a structure, one can extract useful information, as structural degradation and ongoing damage development. These measurements are made at INCAS, Mechatronics Lab.

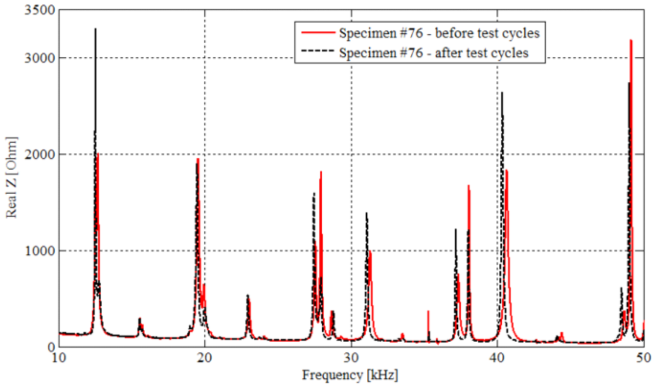


Fig. 2. EMIS signature for specimen disk #76 with defect of arc type, before and after subjecting to radiations and extreme temperatures cycling

3. INVESTIGATION OF DAMAGE CAUSES

Since the EMIS signature does not always clarify the origin of the defects – mechanical or electronic, generated by fatigue and the aging of the structure, or by deficiencies of sensors bonding on the specimen etc, special investigative means were added. It was considered that possible causes of EMIS signature changes were a) fatigue and aging of the mechanical structure due to vibration, b) unfulfillment of an adequate bonding of PWAS to the specimen, and c) damage of PWAS itself.

Transducer health monitoring is required besides structure health monitoring in order to ensure good results. Also, investigations on the adhesive layer are recommended. Thus, there are six areas of interest: the PWAS surface which is investigated with a **digital microscope** and the three involved materials – inside the PWAS, the adhesive layer and inside the aluminum disc structure – investigations done using a **scanning acoustic microscope (SAM)**. Furthermore, the interface between PWAS and adhesive, and the interface between adhesive and aluminum specimen require special attention to provide a good PWAS-specimen contact. Fig. 3 is an exemplification of these six areas.

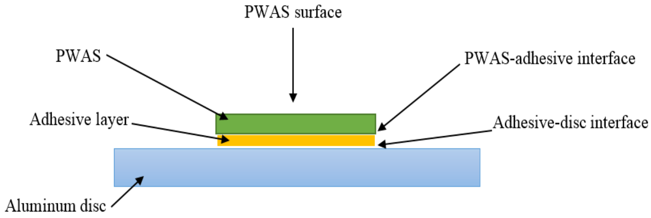


Fig. 3. The six areas of interest for monitoring the PWAS-adhesive-aluminum specimen system's health

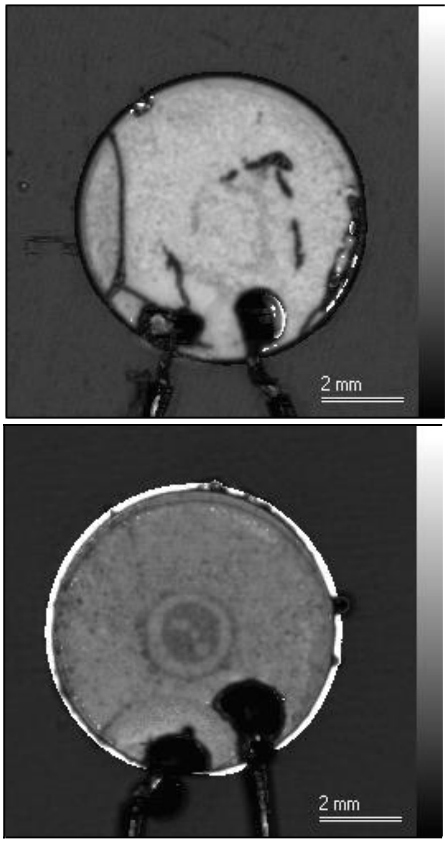
(a)

(b)

Fig. 4. Images obtained with digital microscope VHX 5000 for (a) disk #106 (resolution 30X) and (b) the enlarged image where it can be seen the crack into the left side of PZT

A second system used in measurement and analysis was the *VHX 5000* digital microscope. The VHX is an all-in-one microscope that incorporates observation, image capture, and measurement capabilities. Fig. 4 shows two images of the disk #106 obtained with this device. The picture (b) is an enlarged image of PZT seen in picture (a), where a crack is shown in the left side of the PZT.

Another tool used was the *SAM 300* scanning acoustic microscope. This is mainly dedicated to high throughput, non-destructive analysis for quality control and research applications. The system enables detailed acoustic investigations through new radio frequency and transducer technologies of up to 400 MHz. Built to industry standards around a core platform that utilizes the latest production and research technology, the SAM 300 series has an ultrasound frequency range up to 500 MHz with transducers in the range 5 MHz – 400 MHz. Scanning range: x = 250 µm - 320 mm, y = 250 µm - 320 mm, z = 100 mm.



(a)
(b)

Fig. 5. Images obtained with SAM 300 scanning acoustic microscope at investigating the interface between the PWAS and the epoxy adhesive for (a) the disk #106 (a “bad” bonding) and (b) the disk #138 (a “good” bonding)

Fig. 5 presents images obtained with this device, at investigating the disk #106, particularly chosen wrong, for study. One can see: cracks in PZT (in the electrodes area), a broken piece of PZT (it is visible, also, using the digital microscope (Fig. 4(a)), and areas without glue (Fig. 5(a)). There is a comparison between a “good” and a “bad” bonding. In the case of a “good” bonding (Fig. 5(b)) the adhesive layer is uniformly distributed, there are no delamination areas or cracks in PWAS. The white circle around the PZT shows that the ceramic layer on the top of the PWAS does not cover the entire transducer. In Fig. 4(a) this fact is visible.

Finally, a third device used was the *Polytec PSV-400*. This is a **scanning laser-Doppler vibrometer (SLDV)** – a precision optical transducer used for determining vibration velocity and displacement at a fixed point. The technology is based on the Doppler-effect: sensing the frequency shift of back scattered light from a moving surface. The SLDV was used in order to obtain the vibration motion of the discs at different excitation frequencies corresponding to the resonance frequencies peaks given by the EMIS signature. The SLDV works by scanning the vibrations of a specimen on preset grid by a laser beam based on the Doppler Effect. The vibration mode can be evaluate after applying an electrical pulse to the PWAS and setting a few parameters on the scanning grid points of the specimen. The specimen was placed on a foam layer to be free to vibrate to vibrate as freely as possible and to obtain accurate results.

Fig. 6 shows one of the multiple recordings done in *time domain* with SLDV. The specimen disk # 138 (with arc type defect at 15 mm) is scanned at a frequency of 2.73 kHz, see a 3D representation. The displacement is given in [nm], depending on time [ms] (vibration measured in the z-direction, perpendicular to the disk, takes also negative values). The graph refers to a vibration of a specific point on the surface of the disk otherwise indicated in the picture.

It can be seen that the displacements in the vicinity of the fabricated crack are much bigger than all the other points of the disk producing distinct peak in the EMIS signature.

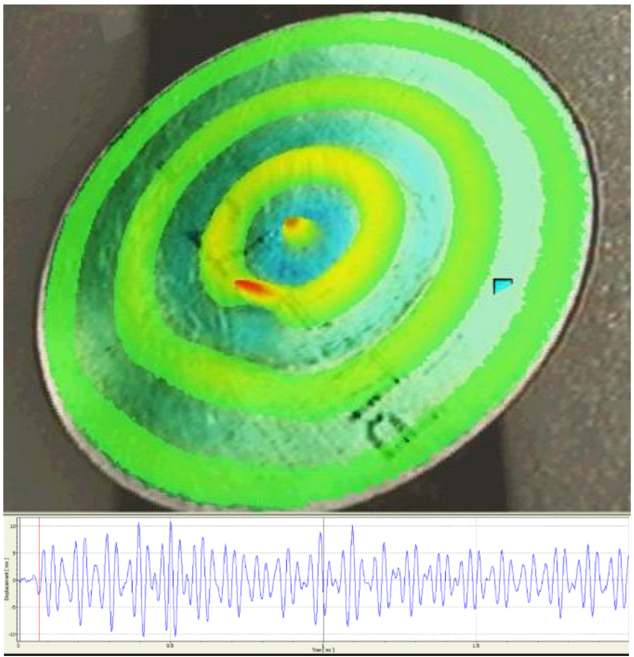


Fig. 6. Recordings in time domain done with SLDV on specimen disk #138 (the registration below indicates a certain stabilization of vibration for the indicated point – blue square)

Fig. 7 shows the use of SLDV for records in the *frequency domain*. For the same specimen # 138, a 3D image of the vibration at a frequency of 49.56 kHz is shown. The displacement graph is associated to a certain point on the disk and indicates the vibration of this point depending on the frequency.

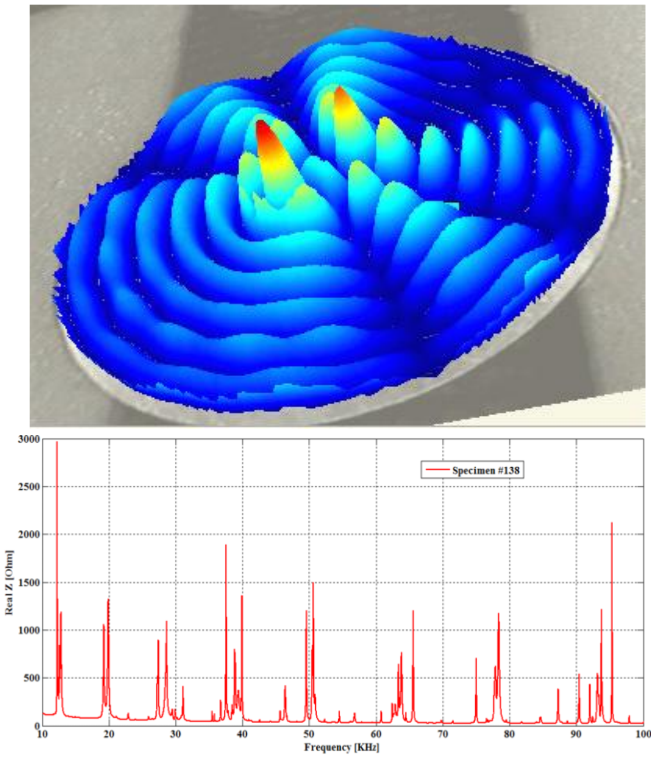


Fig. 7. Recordings in frequency domain done with SLDV on specimen disk #138. Below is given the EMI signature of the disk

4. CONCLUSIONS

One of the major ambitions of modern engineering is to perform SHM in real time in components of high cost and reliability. Thus, the creation or improvement of techniques that enhance the accuracy and reliability of the SHM in Space applications is highly desirable [7].

A first conclusion of the complex tests to validate SHM technology in harsh conditions: EMIS signature shows that some specimens were taken out of service, after completing tests in harsh conditions. Careful diagnosis of these faults is in the process of being made, but we can already say that a leading cause for the specimen decommissioning is the lack of a standardized procedure for bonding the sensor on structure. This drawback is well illustrated by measurements and analyzes made by the two microscopes.

Another result of the paper concerns a quick identification of the simulated damage on the structure specimen using the SLDV (Scanning Laser Doppler Vibrometer), and detailed analysis of the PWAS transducer using the digital microscope and the SAM (Scanning Acoustic Microscope).

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