Towards spacecraft applications of structural health monitoring

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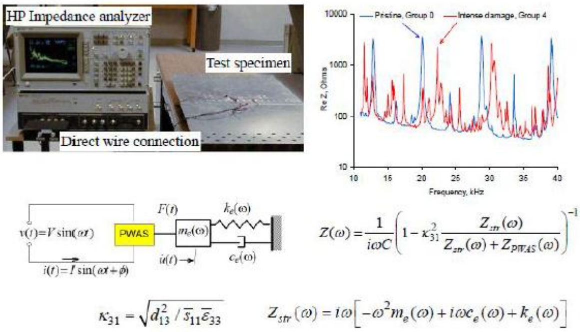
Abstract: *The first part of the paper presents recent developments in the field of structural health monitoring (SHM) with special attention on the piezoelectric wafer active sensors (PWAS) technologies utilizing guided waves (GW) as propagating waves (pitch-catch, pulse-echo), standing wave (electromechanical impedance), and phased arrays. The second part of the paper describes the challenges of extending the PWAS GW SHM approach to in-space applications. Three major issues are identified, (a) cryogenic temperatures; (b) high temperatures; and (c) space radiation exposure. Preliminary results in which these three issues were address in a series of carefully conducted experiments are presented and discussed. The third part of the paper discusses a new project that is about to start in collaboration between three Romanian institutes to address the issues and challenging of developing space SHM technologies based on PWAS concepts. The paper finishes with conclusions and suggestions for further work.*

Key Words: *structural health monitoring, SHM, piezoelectric wafer active sensor, PWAS, spacecraft, guided waves, GW, Lamb waves, extreme space temperatures, radiation exposure; embedded ultrasonic structural radar, EUSR*

1. RECENT DEVELOPMENTS IN THE FIELD OF SHM

In the last decade of the 20th century and the first decade of 21st century the concept of using structural health monitoring (SHM) systems in association with predictive maintenance (PdM) and fault detection (FD) systems has shown a rapid development due to safety demands in all areas of activity, especially in aerospace applications, chemical industry, nuclear power plants, etc. Besides its obvious relevance to the air and space industry, SHM, PdM and FD have become a “must” for many other industries due to increasing productivity and quality demands (zero-defects manufacturing). To emphasize the dimension of this engineering challenge, it is worth noting the prevention of industrial accidents and the increasing cost of scheduled and unscheduled maintenance action for an aging infrastructure has risen to astronomical levels, e.g., up to **27 billion pounds every year** in the British economy [1]. The introduction of SHM, PdM and condition based maintenance (CBM) is viewed as a major milestone in R&D activities because it would results in considerable cost savings together with enhanced safety and increased availability. Smart structures (also referred to as intelligent structures or adaptronic structures) could be the embodiment of SHM, PdM, and CBM concepts because the integration of actuators, sensors, and controls into a smart structure enables the realization of SHM, PdM, CBM concepts in a concise and const-effective way that, in addition, results in novel properties at meso and macro levels.

SHM consists of (a) the observation of a structural system over time with periodical readings using sampled dynamic response measurements from sensors, (b) the extraction of damage-sensitive features from these measurements, and (c) the statistical analysis of these features to determine the current state of health at the structural and system levels. For long term SHM, the output of the process is periodically updated with information regarding the ability of the structure to perform its intended function in spite of the inevitable aging and degradation resulting from operational environments [2], [3], with the benefit to managing the structures *life prognosis and reducing life-cycle costs*. SHM will be one of the major contributions for future smart structures [4].



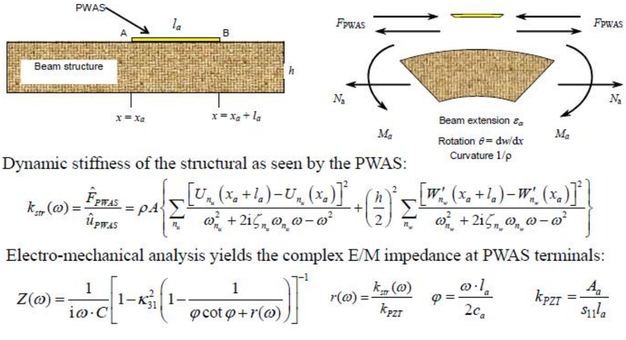
$$Z(\omega)=\frac{1}{i\omega C}\left(1-\kappa_{31}^2\frac{Z_{str}(\omega)}{Z_{str}(\omega)+Z_{PWAS}(\omega)}\right)^{-1}$$

$$\kappa_{31}=\sqrt{d_{13}^2/\bar{s}_{11}\bar{\varepsilon}_{33}} \qquad Z_{str}(\omega)=i\omega\left[-\omega^2 m_e(\omega)+i\omega c_e(\omega)+k_e(\omega)\right]$$

Fig. 1a) – Basics of the E/M Impedance Method

Conceptual SHM approaches are based either on the *structure vibration* or on the structure seen as a *guide of ultrasonic wave propagation*. Thus, the structure is assumed to be instrumented with an array of actuators and sensors to excite and record its dynamic response, including vibration and wave propagation effects.

In the vibrational approach, the data consist of the modal response of the structure produced by the actuators while in the wave propagation approach, they are the broadband signals due to ultrasonic waves propagating in the structures.



Dynamic stiffness of the structural as seen by the PWAS:

$$k_{str}(\omega)=\frac{\hat{F}_{PWAS}}{\hat{u}_{PWAS}}=\rho A\left\{\sum_{n_u}\frac{\left[U_{n_u}(x_a+l_a)-U_{n_u}(x_a)\right]^2}{\omega_{n_u}^2+2i\zeta_{n_u}\omega_{n_u}\omega-\omega^2}+\left(\frac{h}{2}\right)^2\sum_{n_w}\frac{\left[W'_{n_w}(x_a+l_a)-W'_{n_w}(x_a)\right]^2}{\omega_{n_w}^2+2i\zeta_{n_w}\omega_{n_w}\omega-\omega^2}\right\}$$

Electro-mechanical analysis yields the complex E/M impedance at PWAS terminals:

$$Z(\omega)=\frac{1}{i\omega\cdot C}\left[1-\kappa_{31}^2\left(1-\frac{1}{\varphi\cot\varphi+r(\omega)}\right)\right]^{-1} \quad r(\omega)=\frac{k_{str}(\omega)}{k_{PZT}} \quad \varphi=\frac{\omega\cdot l_a}{2c_a} \qquad k_{PZT}=\frac{A_a}{s_{11}l_a}$$

Fig. 1b) – 1-D Modeling of E/M Impedance Method

Both types of signals are affected by the presence of defects [5]. The *electromechanical (E/M) impedance method* is intermediate versus two approaches mentioned above. The paper [6] establishes analytical basics of the method: *the signature of structure's health is seen as the real part of electromechanical impedance curves of a piezoelectric wafer active sensors (PWAS) piezo sensor bonded on structure* (Fig. 1).

PWAS methodology used for structural sensing [7]-[9] includes (a) *standing Lamb waves* (E/M impedance), (b) *propagating and tuning Lamb waves*, and (c) *phased arrays* (Fig. 2). Reference [7] was established the PWAS *tuning principles* for excitation or detection of selective Lamb wave modes through a combination of frequency, PWAS size, and Lamb mode wavelength and proved it by rigorous theoretical analysis, numerical simulations, and experimental validation:

$$\varepsilon_x(x,t)=\frac{1}{2\pi}\frac{-i}{2\mu}\int_{-\infty}^{\infty}\left(\frac{\tilde{\tau}N_S}{D_S}+\frac{\tilde{\tau}N_A}{D_A}\right)e^{i(\xi x-\omega t)}d\xi$$

$$u_x(x,t)=\frac{1}{2\pi}\frac{-i}{2\mu}\int_{-\infty}^{\infty}\frac{1}{\xi}\left(\frac{\tilde{\tau}N_S}{D_S}+\frac{\tilde{\tau}N_A}{D_A}\right)e^{i(\xi x-\omega t)}d\xi$$

$$N_S=\xi q(\xi^2+q^2)\cos ph\cos qh,\quad D_S=(\xi^2-q^2)^2\cos ph\sin qh+4\xi^2pq\sin ph\cos q$$

$$N_A=\xi q(\xi^2+q^2)\sin ph\sin qh,\quad D_A=(\xi^2-q^2)^2\sin ph\cos qh+4\xi^2pq\cos ph\sin q$$

$$\varepsilon_x(x,t)=-i\frac{a\tau_0}{\mu}\sum_{\xi^S}\sin\xi^S a\frac{N_S(\xi^S)}{D_S'(\xi^S)}e^{i(\xi^S x-\omega t)}-i\frac{a\tau_0}{\mu}\sum_{\xi^A}\sin\xi^A a\frac{N_A(\xi^A)}{D_A'(\xi^A)}e^{i(\xi^A x-\omega t)}$$

Mode tuning capabilities

relationship that is a customization of general solution [9]

$$\varepsilon_r(r,t)\big|_{z=d}=\pi\frac{\tau_0 a}{\mu}e^{i\omega t}\left[\sum_{\xi^S}J_1(\xi^S a)\xi^S\frac{N_S(\xi^S)}{D_S'(\xi^S)}H_1^{(2)}(\xi^S r)+\sum_{\xi_A}J_1(\xi^A a)\xi^A\frac{N_A(\xi^A)}{D_A'(\xi^A)}H_1^{(2)}(\xi^A r)\right]$$

The PWAS tuning principles were subsequently applied to the detection of various damage types such as crack, corrosion, and delamination by enhancing detectability through the selection the Lamb-wave mode most sensitive to a certain damage type.

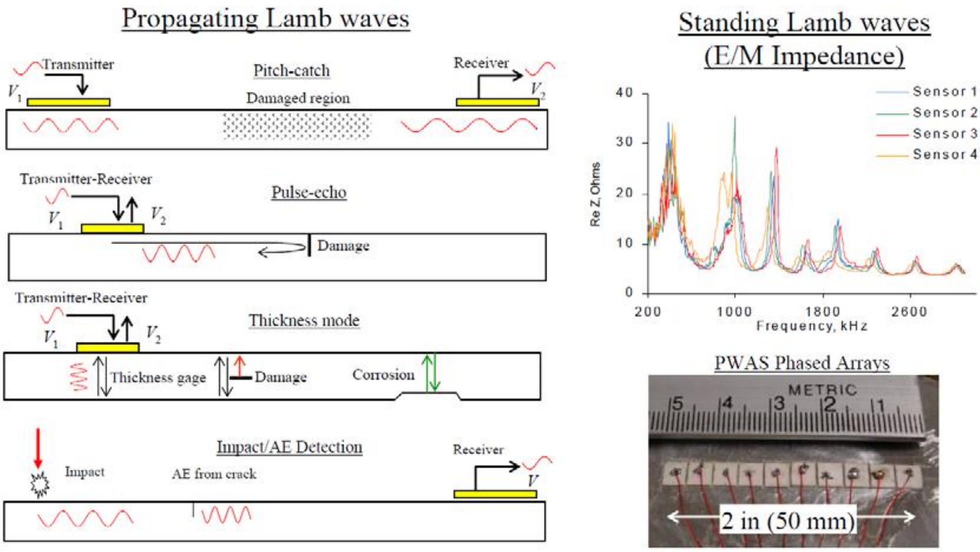


Fig. 2 – E/M Impedance method in the general framework of Lamb waves

Another result concerns the PWAS *phased arrays concept*, that combines the phased-array principle with the above-mentioned PWAS tuning principle to generate steered beams of single-mode low-dispersion guided waves (GW) traveling in thin-wall structures. Although phased arrays have been used in conventional *nondestructive evaluation* (NDE) with *bulk waves*, the idea has been to use this principle with PWAS transducers and GW, which was made possible by previous cited work on PWAS tuning [7]. Also referred "*embedded ultrasonics structural radar (EUSR)*", this method has been proven successfully on simple geometries and on actual aircraft parts (Fig. 3).

The connection between structures vibration and SHM as a cause-effect relationship is almost axiomatic and needs not be argued. However, most of the published literature addresses SHM and active structural control separately, as distinct and independent tasks in the resolution of a technical problem. Only few works researchers have addressed simultaneously these two aspects of the problem as for example ref. [12], in which a synergic simultaneous application and operation of these two methodologies is implemented. Fig. 4a)

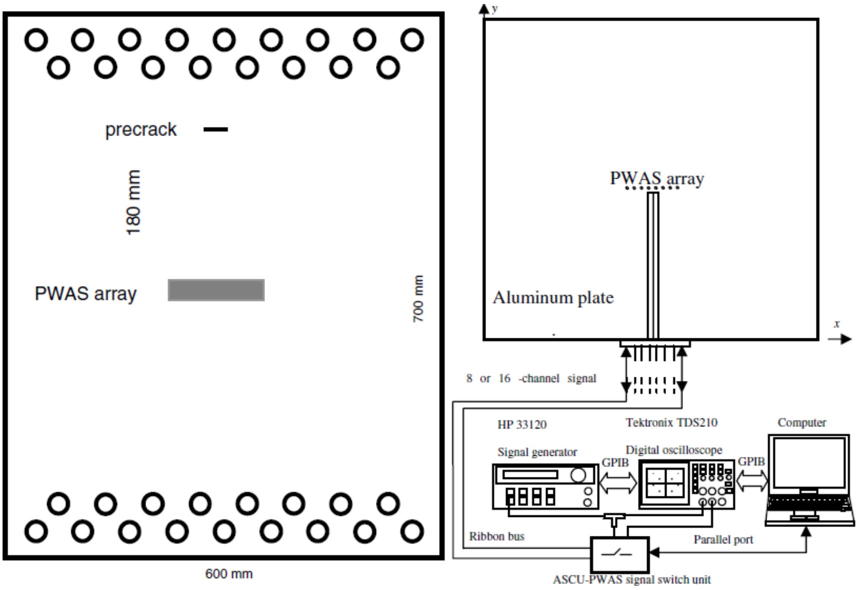
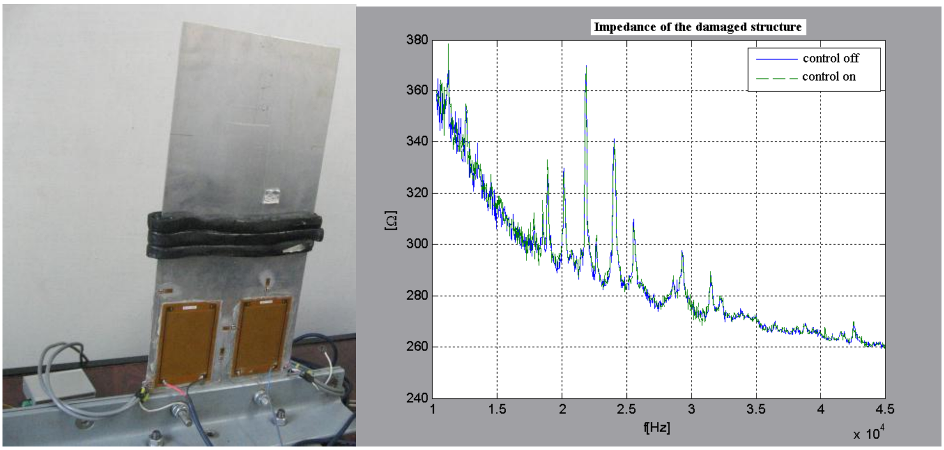


Fig. 3 – Schematic of experimental setup for fatigue testing with PWAS array and EUSR algorithm to achieve insitu monitoring of fatigue crack growth [11]



a) b)

Fig. 4 – a) Experimental model for SHM strategy with simultaneously active vibration control; b) E/M impedance signature [12]. A PNCDI2 Project (code 81 031, 2007-2010)

shows a proof-of-concept demonstrator of this idea, in which an aluminum cantilever plate with Macro Fiber Composite (MFC) bonded on the structure.

Modeling clay was attached to the specimen to simulate damage. The measured signature signal used to assess the structural health was the real part of E/M impedance spectrum of a MFC piezo sensor (Fig. 4b). Active control laws based on the optimal Linear-Quadratic Gaussian (LQG), LQG/LTR (Loop Transfer Recovery) (Fig. 5), or H_∞ synthesis [13], [14], [15] were used. Just one MFC actuator and one monitoring MFC sensor were sufficient to implement this strategy (Fig. 6a). Other hardware components of the experimental setup for these tests are shown in Fig. 6b.

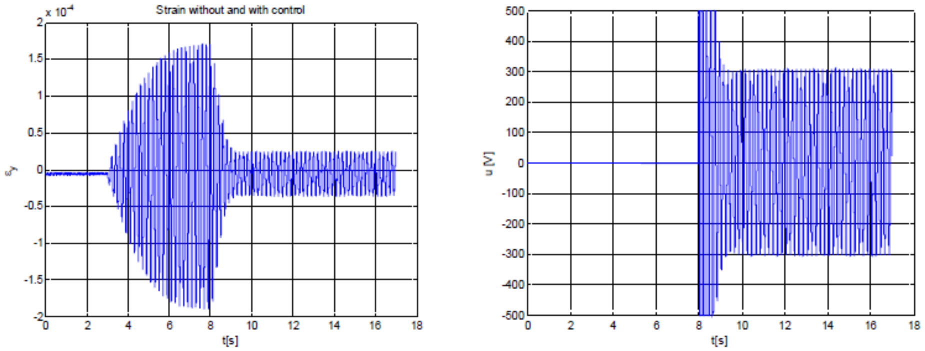
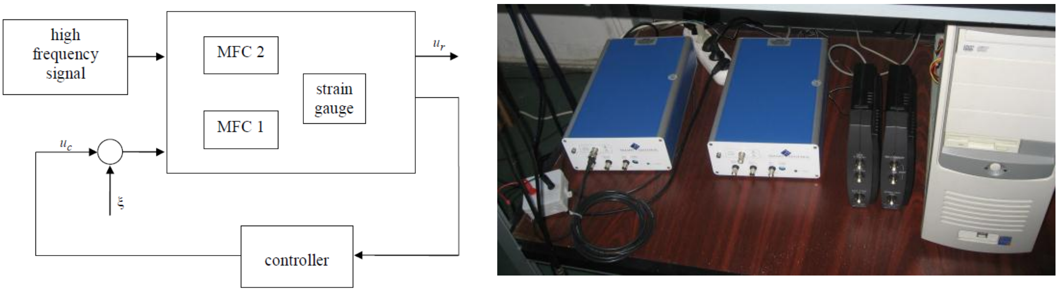


Fig. 5 – The efficiency of LQG/LTR control, experimental record [12]

It is apparent from this brief review of the *state of the art* that theoretical developments and laboratory tests have verified that the various modes of operation of the PWAS transducers [9]. Various PWAS GW SHM methodologies have been developed to date, such as (a) embedded GW ultrasonics (pitch-catch, pulse-echo, phased arrays, thickness mode waves propagation); and (b) high-frequency modal sensing, i.e., the E/M impedance. For large area scanning, a PWAS phased array was used to monitor fatigue crack growth using the EUSR algorithm. For quality assurance, PWAS self-test with the E/M impedance method was developed. We need to mention that our brief review of the SHM state of the art has mostly addressed the work done by the authors of this article. Other important research directions and results exist but they could not be retained here for reasons of space.



a) b)

Fig. 6 – a) The strategy of simultaneously SHM and active control; b) hardware components of the test rig for SIMCA tests

Based on the extensive SHM literature developed in the last 15 years, it can be argued that this field has matured to the point where fundamental axioms and general principles have emerged; for example, ref. [16] enumerates several SHM fundamental axioms, from which we cite the following:

a) *Axiom IVa*: Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information.

b) *Axiom IVb*: Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions.

c) *Axiom V*: The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system.

The above brief review of the state of the art in PWAS GW SHM technologies indicate that significant research results have been achieved in demonstrating this technology for aeronautical applications. Crack detection in an aircraft panel with PWAS transducers operating in pulse-echo, phased-array, and E/M impedance methods were illustrated. The PWAS GW SHM technology has been shown capable of detecting damage in actual metallic and composite specimens resembling actual airframe components. It seems apparent that, in aeronautical applications, SHM technologies are at *Technology Readiness Level* (*TRL*) 2-3, i.e., they are moving from successful laboratory developments into on-vehicle proof-of-concept demonstrations to address specific "hot-spot" problems. The transition of PWAS GW SHM technologies into on-aircraft tests is underway (see, for example, Acellent Technologies Inc., http://64.105.143.179/).

2. BEGINNING SHM RESEARCH FOR SPACE APPLICATIONS

Our brief SHM literature survey has also revealed that only very few references are dedicated to space applications of SHM technologies [18], [21], [22], [26]. Although paradoxical, the reality is that the approach of SHM space technologies records only the first attempts. **Columbia shuttle accident** Fig. 7a has raised several questions about the possible use of sensors for in-space SHM [17]. To illustrate the state of the art, we mention here the case of the Columbia Space Shuttle accident. After the Columbia Accident Investigation Board issued its report in August 2003, NASA decided to add sensors to the Space Shuttle to detect any blows from debris and to produce alerts if leading edges of the wings were hit. However, these sensors were not sufficiently advance to determine the degree of damage, as indicated by Joseph Cuzzupoli, a Kistler Aerospace Corp. vice-president. The extent of damage would still have to be determined by an inspection by astronauts in orbit using an extension boom equipped with cameras and lasers.

The interest in space SHM is slowly catching on and is not yet showing in major SHM reference books: for example, the syntagma of "Space SHM" is not appearing in the Table of Contents of the 2009 SHM encyclopedia [20].

Two explanations may exist for this situation: first, the recent slowdown in Space activities in comparison with the tremendous Apollo Program of the years 1960-1970 after the Challenger and Columbia Disasters. Second, the possibility of a simplistic assumption that Space SHM technologies could be achieved as trivial extensions of the terrestrial and aeronautical SHM technologies.

This assumption is not quite valid because of the many differences between aeronautical and space SHM requirements, as discussed later in this section. The development of SHM technologies specific to Space applications is necessary in order to address the specificity of in-space operation defined by extreme environmental conditions typical of the in-space temperature cycles and by the exposure to space radiation as well as by the high vacuum environment and the presence micro meteorite impacts.

At present, it is expected that the conquest of Space will increase at an accelerated pace in the decades to come with the advent of commercial space ventures and interests. Subsequently, we also expect that the interest in developing space SHM technologies will also grow.

PWAS SHM technologies have a good potential for use in spacecraft SHM applications and in-orbit structural safety assessment. In rest of this section, we will summarize some recent results in this direction.

The behavior of PWAS transducers at very cold (cryogenic) and hot temperatures as well as under exposure to space radiation is very important for the successful implementation of these technologies in space applications. Several experimental studies were recently performed, as described in ref. [21], [22], [26].

a) b) c)

Fig. 7 – a) A shower of foam debris after the impact on Columbia's left wing. The event was not observed in real time [17]. b) Cryogenic survivability specimens: carbon/epoxy composite specimen having several PWAS transducers for pitch–catch wave propagation testing [22]; c) Liquid N_2 immersion setup for wave propagation testing showing the specimen being prepared for submersion in liquid N_2 [22]

2.1 PWAS experiments at cryogenic temperatures

A set of experiments were performed in which *cryogenic conditions* were reproduced by the use of special containers filled with liquid N_2, which ensure a cryogenic temperature around $-200^\circ C$. The set of experiments were divided into two groups. The aim of first set of experiments was to determine the CT operability of a PWAS-based SHM approach for composite materials. The aim of second set of experiments was to perform damage detection with a PWAS-based SHM system operating on composite specimens subjected to cryogenic conditions. Round PWAS transducers (7 mm in diameter, 0.2 mm in thickness, American Piezo Ceramics APC-850 material) were used. It was shown that the piezoelectric material APC-850 and the PWAS transducers are able to retain their operational abilities after exposure to cryogenic conditions. Free PWAS resonators as well as PWAS transducers attached to metallic plates were submerged in liquid N_2 at cryogenic temperatures (CT), kept there for 10 min before measurements to test the survivability, and had their E/M impedance signature taken.

Then, they were returned to room temperatures (RT) and had the E/M impedance signature taken again. The process was repeated for 10 times with good results. In these studies was used a similar approach but with the focus on composite material specimens. In addition, were also augmented the experiments with pitch–catch measurements besides the E/M impedance measurements.

The adhesive layer between the PWAS and the structure and solder material used to connect the PWAS electrodes to the electric wiring was carefully selected. A strip of unidirectional carbon/epoxy composite material was used to test the PWAS pitch–catch operability at CT. Fig. 7b shows the specimen with several PWAS transducers attached to it; Fig. 7c shows the experimental setup. Fig. 8 shows the impedance signatures. From the recorded data, it can be seen that the SHM system impedance curves did not change significantly after submersion in liquid N_2; the peak amplitude and their relative frequency location seem to remain the same throughout the experiment. Fig. 9 shows pitch–catch wave propagation before, during, and after submersion of the specimen in liquid N_2.

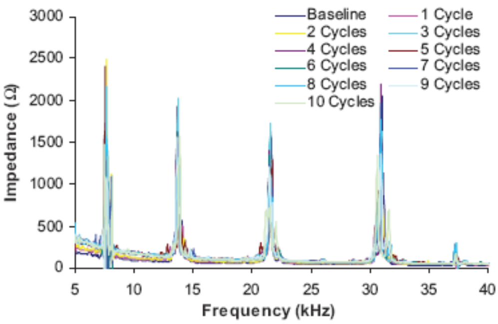


Fig. 8 – Indication of survivability through resumption of resonant properties after submersion in liquid nitrogen (PWAS, AE-15, RT) [22]

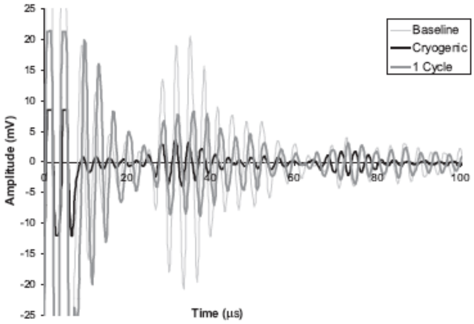


Fig. 9 – Wave propagation in composite for various thermal environments; comparison of a wave packet before, during, and after submersion in liquid N_2 [22]

The data collected showed that the PWAS was able to send and receive signal at CT. However, when the specimen was submerged in the liquid nitrogen, the amplitude of the wave packet decreased. This behavior is consistent with studies performed elsewhere, which showed that fluid coupling can reduce the Lamb wave propagation velocity and amplitude [23]. In this study [23], it is apparent that the effect of submerging the specimen into liquid N_2 is twofold: (a) effects that are due to fluid loading and Lamb wave leakage and (b) effects that are due to CT. In the papers [21], [22] the focus has been on the latter effects, that is, on how the CT might influence the performance of the PWAS transducers. The data shown in Fig. 8 indicate the following: (a) PWAS transducers are still active at CT and are able to transmit and receive guided Lamb waves into the specimen and (b) nonetheless, a specimen with pitch–catch PWAS attached to it behaves differently at RT after exposure to CT by submersion in liquid N_2 than before submersion. Fig. 8 shows that the wave amplitude after submersion is lower than before submersion. (When submerged in liquid N_2, the wave amplitude is even lower because of the additional wave leakage effect.) As noted in the cited papers, we are not sure at this stage why this reduction in performance happens after submersion in liquid N_2 and return to RT, but we believe that it is not due to a degradation in piezoelectric properties of the piezoceramic material because separate tests performed on free PWAS transducers indicated that there is no performance degradation to the piezoelectric material after cryogenic exposure through submersion in liquid [21]. Hence, we believe that the decrease in performance could be attributed to a degradation of the adhesive bond between the PWAS and the specimen due to the differential coefficient of thermal expansion (CTE) between the two materials. *This aspect needs further investigation; we plan to do it as soon as practically possible if further funding is available; we will report such new results in a future communication.*

2.2 PWAS experiments at high temperatures

The effects on PWAS of *high temperatures* (HT) are equally important to know. Three requirements significant for HT piezoelectric applications would be the Curie transition temperature, the pyroelectric properties, and the ferroelectric properties [24]. In the same paper [20] are reported the outcomes of thorough testing of free or bonded PWAS to a series of HT in an oven for 30 min time intervals. After each 30 min, the PWAS was cooled and their impedance spectrums were measured in RT. Fig. 10 shows the real part impedance spectrum of a free PWAS measured in RT and the real part impedance spectrums of the PWAS after exposure to oven temperatures ranging from 38 to $371^\circ\mathrm{C}$ with $38^\circ\mathrm{C}$ increment.

The Curie temperature for PZT PWAS is 329°C. As seen in the Fig. 10, under 260°C, the real part impedance spectrums of PWAS possesses two strong antiresonant peaks due to the intrinsic E/M impedance of the free PWAS. With the further increment of oven temperature PWAS lost its piezoelectric effect, which is manifested by the loss of antiresonance peaks in real part impedance spectra. The tests have shown the free PWAS was able to maintain its antiresonance peak amplitude at the RT after the short-term heating up to 260°C. This suggested that free PWAS can survive after heating up to 260°C.

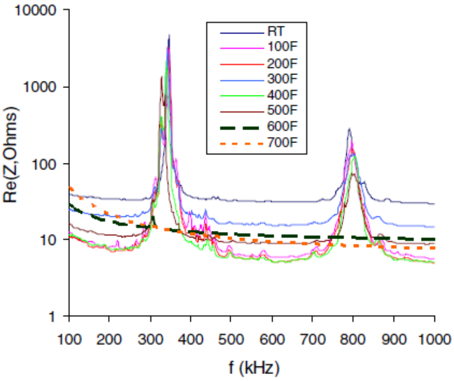


Fig. 10 – Indication of free PWAS survivability at HT [21]

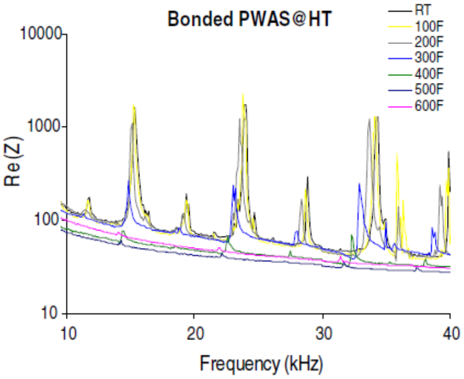
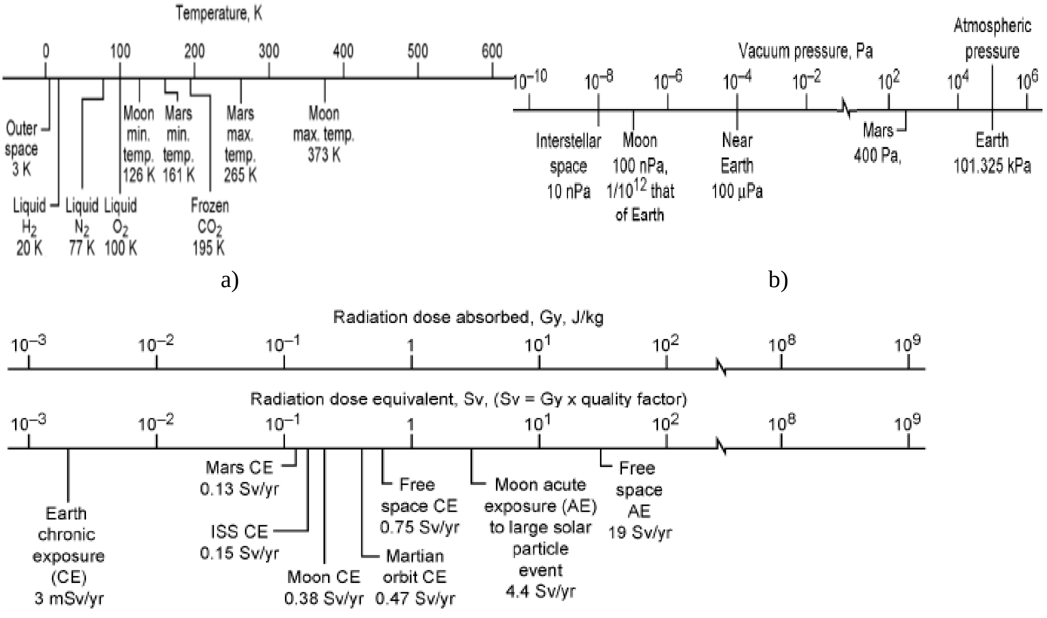


Fig. 11 – Indication of bonded PWAS survivability at HT [21]

A bonded PWAS was subjected to high temperature in the oven with the similar setup as the free PWAS. Because of the HT, extra was taken for the bonding of sensors. Vishay adhesive M-Bond 610 has a short-term operating temperature range from –269 to +371°C and a long-term operating temperature range from –269 to +260°C. The PWAS durability test for bonded PWAS at high temperature used M-Bond 610 adhesive. PWAS impedance spectrums were measured at the oven. Fig. 11 shows the real part impedance spectrum of the bonded PWAS after exposure to oven temperatures ranging from 38 to 316°C with 38°C increment. As can be seen, the real part impedance spectrums of bonded PWAS antiresonant frequencies and amplitudes reduced after increasing the temperature. At temperature above 204°C, the real part of impedance spectrum becomes very small. After reaching the Curie temperature, the bonded PWAS lost its piezoelectric effect. The tests have shown the first antiresonance peak amplitude remain the same when the environmental temperature was below 93°C. The amplitude started to drop above 93°C. However, this drop is not as abrupt as noticed for free PWAS above 260°C.

This suggests that the performance of PWAS bonded to aluminum plate with M-Bond 610 adhesive is constant up to 93°C and starts to degrade thereof. The earlier onset of degradation for bonded PWAS in comparison to free PWAS may be attributed to 1) softening of organic adhesive due to temperature and 2) mismatch of thermal expansions between PWAS and structural substrate. Therefore, *further studies, including temperature cycling, would be necessary to quantify these outputs*. (A breviary of temperature variation in Space, completed for compliance with a range of the vacuum pressure description, are given in Figs. 12a), b)). The preliminary conclusion would be that lead zirconate titanate piezoelectric wafer active sensors can be successfully used in a cryogenic environment, but it does not seem to be a good candidate for high temperature. This emphasizes the importance of achieving the proper design of the adhesive bond between the PWAS and the structure, and of using a protective coating to minimize the ingression of adverse agents.



a) b)

c)

Fig. 12 – a) Range of the temperature in space; b) range of the vacuum pressure in space; c) range of the absorbed dose in space [25]

Worthy to note the high-strain tests indicated that the PWAS transducers remained operational up to at least 3000 microstrain and failed beyond 6000 microstrain. In the fatigue cyclic loading, conducted up to 12 million of cycles, the piezoelectric wafer active sensor transducers sustained at least as many fatigue cycles as the structural coupon specimens on which they were installed [21].

2.3 PWAS experiments under ionizing radiation

We continue to report also preliminary results on the behavior of PWAS transducers under exposure to *ionizing radiation in the framework of nuclear reactors,* were recently published in the paper [26]. Here are interested in a brief classification of cosmic radiations. The cosmic rays may broadly be divided into two categories: primary and secondary. The cosmic rays that originate from astrophysical sources are primary cosmic rays; these primary cosmic rays interact with interstellar matter creating secondary cosmic rays.

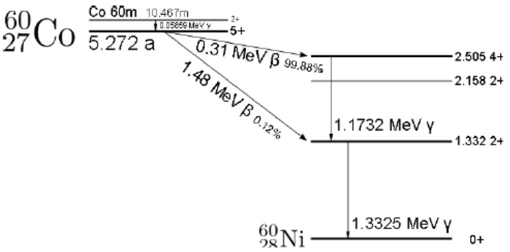
The Sun also emits low energy cosmic rays associated with solar flares. Almost 89% of cosmic rays are protons (^{1}H nucleus), about 9% are helium nuclei (α particle), and nearly 1% is electrons (β particles) and 1% represent other ionizing radiations like neutron, gamma rays, etc.

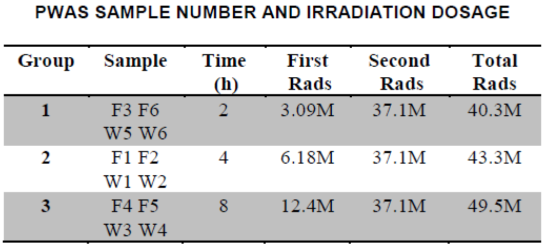
Charged particles (α, β, p) and gamma rays interact with electrons of the mater and ionized atoms/molecule directly. Neutral particles, like neutron, interact with atom nucleus, ionized atoms/molecules indirectly. The gamma rays are penetrating radiation, permit a relative facile detection/dosimetry and are optimal for uniform and reproducible irradiation experiments. The most used for researches of ionizing radiation effects and industrial irradiations is 60-Co.

In the paper [26], the Co-60 gamma source with a maximum dose rate of rad/hr was used for irradiation test (Fig. 13a)). The absorbed dose was calculated by Monte Carlo modeling (MCNP5), simulating interaction and average specimens density. The predicted dose rate is 1.5447×10^5 Rads/hr. The free and wired PWAS samples under different dosages are shown in Fig. 13b). For the first irradiation tests, 12 samples are separated into three groups. The groups were irradiated for 2, 4, and 8 hours individually. After the capacitance and EMIS measurement after first irradiation, additional 24h (37.1 M rads) were applied for all the 12 PWAS.

A short term irradiation effects for PWAS have been studied. PWAS were exposed to high energy Co-60 gamma radiation and maintained its piezoelectricity in a series of 2-h, 4-h, 8-h, 24-h tests. The visual inspection indicates that a degradation in the electrodes after irradiation. The PWAS capacitance reduced after the first irradiation and increased average 5% after the 24h irradiation.

The E/M I measurement showed that majority of the irradiation effect in the PWAS was developed during the first 8 hours in both free and wired PWAS groups. This preliminary exploratory work has shown that the irradiation decreased the electrical capacitance and the Curie point, and increased the thickness mode resonant frequencies. The observed effects were attributed to a change in the electrode bonding and a reduction in the polarization of the ceramic. *The experiments must be continued to verify the durability and survivability in the long term.* A series of scanning electron microscope (SEM) and X-ray will be performed to identify the changes in the materials.





PWAS SAMPLE NUMBER AND IRRADIATION DOSAGE

Group	Sample	Time (h)	First Rads	Second Rads	Total Rads
1	F3 F6 W5 W6	2	3.09M	37.1M	40.3M
2	F1 F2 W1 W2	4	6.18M	37.1M	43.3M
3	F4 F5 W3 W4	8	12.4M	37.1M	49.5M

Fig. 13 – a) Co 60 source data; b) PWAS samples and irradiation dosage

For endurance evaluation of SHM technologies in specific space conditions, the cosmic rays (simulated using gamma rays), extremely temperatures and vacuum pressure effects should be evaluated simultaneously).

3. SHM IN SPACECRAFT STRUCTURES USING PWAS − A NEW PROJECT

A project is underway in INCAS Elie Carafoli, in partnership with Institute of Solid Mechanics of the Romanian Academy and National Research Institute for Physics and Nuclear Engineering − IFIN Horia Hulubei. The project addresses the SHM of metallic and composite spacecraft structures using guided Lamb waves generated and captured by PWAS. Both propagating waves and standing waves (i.e., structural vibration) will be used for damage identification since these two approaches are complementary to each other. The novelty of the project consists in addressing a hybrid global-local (HGL) approach in which finite element discretization is confined to the local zones around the structural damage whereas wave propagation in the large “clean” areas of the structure is performed with analytical methods (e.g., Green’s functions).

Once developed, this predictive modeling procedure based on the HGL concept will be used to develop damage detection algorithms that will locate the damage and quantify its size and extent from processing the corresponding guided waves transmitted through the structure with the PWAS transducers.

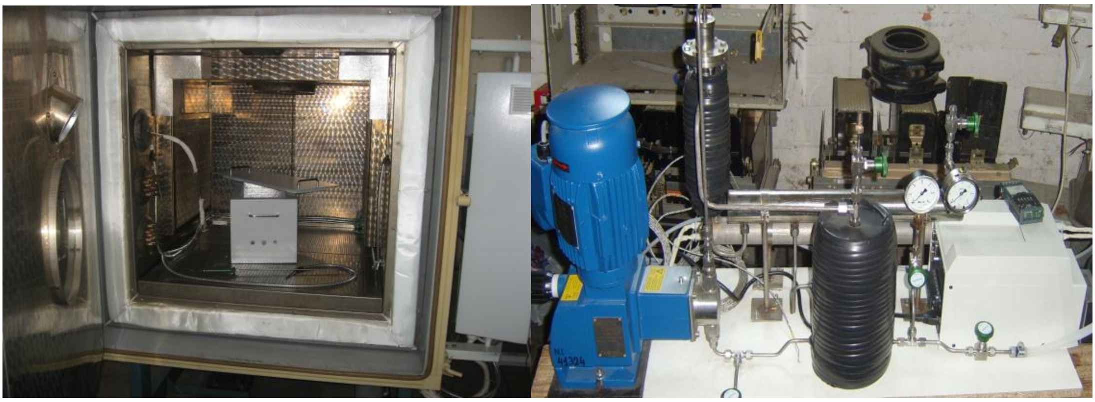


Fig. 14 – a) Photo of INCAS climatic chamber; b) photo of IFIN high vacuum device of Pfeiffer type

The experimental part of the project will address specific to space applications: the extreme temperature variations and space radiations and their effect on the piezoelectric materials used in PWAS transducers. The project will continue preliminary studies of the authors just described in Sections 1, 2 and will perform a comprehensive battery of tests to fully qualify PWAS transducers for SHM use in space operations. Coupon specimens instrumented with an array of PWAS transducers will be exposed to extreme environmental conditions of hot and cryogenic temperatures and ionizing space radiations (Fig. 14). The functionality of the PWAS transducers in transmitting and receiving guided Lamb waves will be verified under these extreme environmental conditions generated in climatic chambers, in liquid N2, and under ionizing radiation.

4. CONCLUDING REMARKS

The transfer of SHM technology to space applications is only in its infancy now, but is expected to will follow the same ascending course as the space industry as a whole. Already, it is estimated that the use of SHM technologies in the aircraft and ground vehicle may increase ten-fold in the coming decades (see the meetings of the SAE Aerospace Industry Steering Committee on SHM and http://www.sae.org/standardsdev/news/P91616.pdf). The application of SHM technologies to space vehicles will be the “next big thing”, with significant implementation funding likely to come on-line in the 2015-2020 timeframe. The first part of the paper presents recent developments in the field of structural health monitoring (SHM) with special attention on the piezoelectric wafer active sensors (PWAS) technologies utilizing guided waves (GW) as propagating waves (pitch-catch, pulse-echo), standing wave (electromechanical impedance), and phased arrays. The second part of the paper describes the challenges of extending the PWAS GW SHM approach to in-space applications.

Three major issues are identified, (a) cryogenic temperatures; (b) high temperatures; and (c) space radiation exposure. Preliminary results in which these three issues were address in a series of carefully conducted experiments are presented and discussed.

The third part of the paper discusses a new project that is about to start in collaboration between three Romanian institutes to address the issues and challenging of developing space SHM technologies based on PWAS concepts. The product and technology that we aim to develop through this research project is new and has not yet been used for spacecraft applications.

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