Integrated Phased Array Transducer for On-Board Structural Health Monitoring

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ABSTRACT

Permanently bonded onto a structure, an integrated Phased Array (PhA II) transducer that can provide reliable electromechanical connection with corresponding sophisticated miniaturized "all in one" SHM electronic device installed directly above it, without need for any interface cabling, during all aerospace structure lifecycle phases and for a huge variety of real harsh service environments of structures to be monitored is presented. This integrated PhA II transducer [1], as a key component of the PAMELA SHM™ (Phased Array Monitoring for Enhanced Life Assessment) system, has two principal tasks at the same time, reliably transceive elastic waves in real aerospace service environments and serves as a reliable sole carrier or support for associated integrated on-board SHM electronic device attached above. The PhA II transducer successfully accomplished both required task throughout extensive test campaigns which included low to high temperature tests, temperature cycling, mechanical loading, combined thermo- mechanical loading and vibration resistance, etc. both with and without SHM device attached above due to RTCA DO-160F.

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INTRODUCTION

Transducers for efficient and reliable Structural Health Monitoring need to fulfill a huge set of physical characteristics, performance requirements and normative compliances in order to be installed on-board of commercial aircraft providing clients with reliable information about any structural changes, be it temporal or permanent, during entire aircraft life cycle. Some of the most important requirements which compliance were tested, verified and validated by AERnnova's through several validation and verification test campaigns on AERnnova's integrated phased array transducers (PhA II) described herein, were: high signal integrity, good signal quality, low signal noise levels, transducer integrity, transducer durability, high transducer capacity to sense ultrasonic waves/events, high transducer capacity to transmit ultrasonic waves/events, high transducer resistance to real service environments (and a bit more), transducer immunity against electromagnetic interferences (emission or susceptibility), sensitivity for other environmental influences and coupling with ultrasonic sensing, high quality of electromechanical connectivity with the SHM equipment, transducer capacity to support the weight & service loads once the SHM device coupled above, etc.

Besides the first objective, to verify PhA II transducers compliance with the aerospace normative and certifying regulations and procedures, performed V&V tests described hereinafter had one additional important objective; to acquire the necessary data base of ultrasonic structural responses (on different host structures, transducers versions, SHM hardware and software used, structure boundary conditions, structure materials, etc.) in different environmental conditions in order to obtain the necessary input for quantification of all adverse effects and acquire an understanding of their influences on guided waves, on wave propagation and distinguish those effects from the damage associated ones.

INTEGRATED PHASED ARRAY TRANSDUCER PhA II

Development of advanced on-board SHM systems based on ultrasonic wave propagation and development of efficient damage detection algorithms for continuous inspection of real aircraft structures requires in the first step a reliable transducer. Due to market availability lack of efficient, reliable and integrated transducer for transceiving of ultrasonic waves in real service environments at the time, AERnnova decided to design and manufacture their own phased array transducers. After design, manufacturing and successful test campaign performed on the first transducer version (PhA I) several innovative features were detected and integrated in the new transducer PhA II. The resulting integrated PhA transducer (version II) consists of a set of aligned piezoelectric discs with wrap around electrodes for transceiving of elastic ultrasonic waves, plurality of electrical traces and contact pads, several layers of a flexible printed circuit board, electromagnetic shielding between channels and overall, one electromechanical multipinned connector with stiffening ring around and all that integrated into one small unit easy for surface installation by conformed bonding and final application on real structures. The main PCB (consisting of plurality of conductive wire traces and electrical contacts) of the PhA II is designed to be able to install different piezoelectric transducers shapes and sizes, and also from different piezoceramics manufacturers (Noliac, etc.). The final exterior aspects of PhA II are shown on Fig.1 and Fig.2 while on the Fig.3 and Fig.4 is shown an example of the transducer surface bonded onto a real aircraft structure, with the integrated SHM "all in one" electronic device (PAMELA III) electromechanically coupled (via Nicomatic CMM220 microconnector) above and supported only by the transducer without any contact with/or need for additional fixation onto the structure.

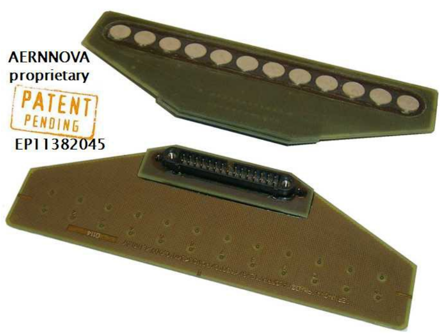

Fig. 1. Integrated PhA II Transducer (underneath and overhead view).

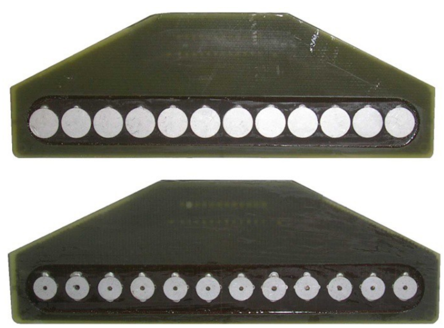

Fig 2. Integrated PhA II transducers with different piezoelectric sizes and shapes (disk or ring).

Fig. 3. An example of PhA II transducer surface bonded onto a CFRP HTP leading edge rib.

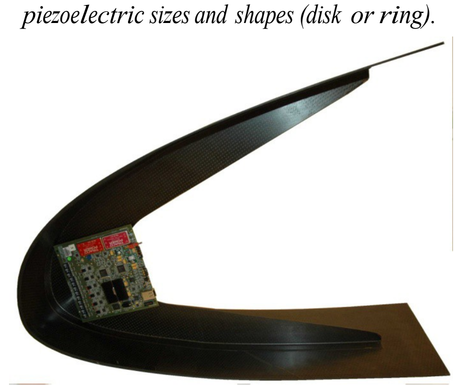

Fig.4. An example of PAMELA III electronic device electromechanically coupled without any contact with structure directly onto the PhA II transducer).

PERFORMANCE VERIFICATION TESTS

An extensive test campaigns were necessary and performed in order to verify and validate transducer performance and fulfillment with set design requirements. An overview of performed tests, objectives, test set-ups and results are presented herein.

Static Mechanical Loading Tests

Besides the two most important test campaign objectives mentioned in the introduction, some additional ones were pursued in static tests. These were: to verify the capacity of damage detection of statically loaded structures by PAMELA SHM™ system, to verify system capacity to distinguish wave changes due to static load effects from the real damage effects, to verify stiffness, durability and resistance of the adhesives used for transducer bonding, to find the optimum adhesive or combination of several and also to find the optimum excitation function. Tests (Fig.5) were performed on aluminum and CFRP specimens in a wide range of one axis tension load levels and for different SHM system test modes. Ultrasonic structural responses were acquired for each load level step up to 70KN, different test set up conditions and all compared a posteriori (Fig.6) verifying structural and signal integrity of the PhA II.

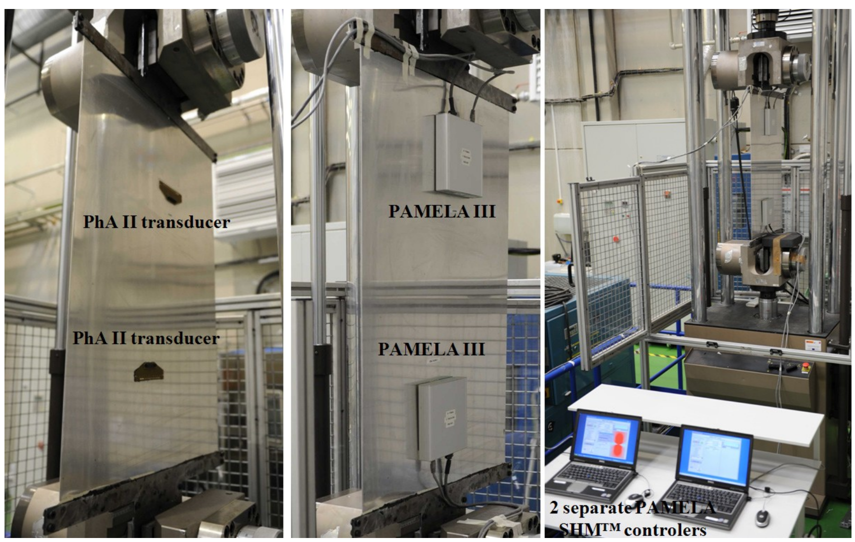

Fig. 5. PAMELA SHM™ system in three steps: PhA II transducers bonding, electromechanical coupling of PAMELA III devices above the transducers and connection with the SHM system controllers.

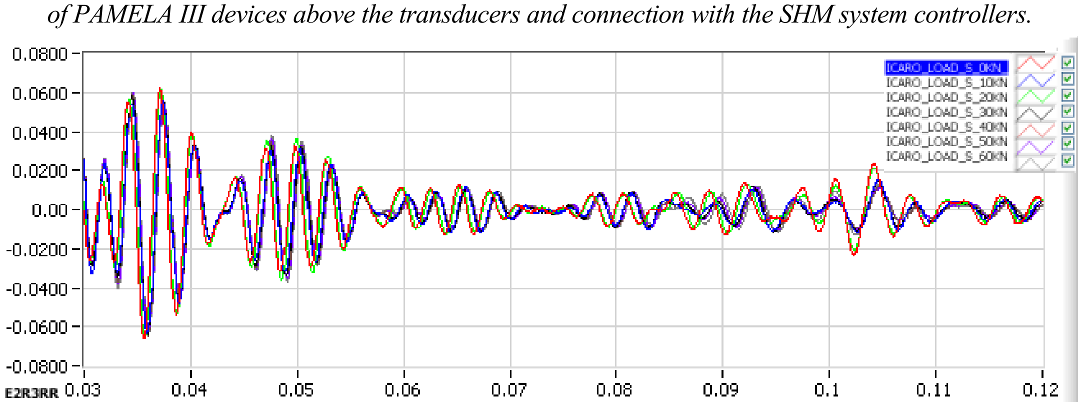

Fig. 6. Zoomed view of one of the response matrix elements for different static load levels.

Dynamic Mechanical Loading Tests (Category Standard & Robust Vibration)

Test objectives perused in vibration tests were: to demonstrate that PhA II transducer and PAMELA III [2] once coupled together comply with the applicable aerospace normative (including durability requirements) when subjected to vibration levels specified for the appropriate installation, to show and verify the reliability of all transducer constituent components after the tests, to verify the stiffness and structural integrity of the electromechanical connection of the PAMELA III electronic PCB in vibration environment, to verify the capacity of damage detection of dynamically loaded structures, to verify the capacity to distinguish wave changes due to dynamic load effects from the damage effects, to verify survivability of PhA II transducers (with and without coupling) due to RTCA /DO-160F normative for category S and R. Tests were also aimed to verify stiffness, durability, resistance and survivability of the adhesive used for transducer bonding and to verify signal integrity on each transducer channel once tests completed for each axis. Fig. 7 shows the test set up where on an aluminum panel, with PhA II transducers bonded and PAMELA III coupled above, was fixed on a shaker for vibration tests (Fig. 8) in vertical direction (and sliding table for horizontal tests). Both frequency response functions and ultrasonic responses were acquired before and after each test condition changes in order to compare and make transducer performance assessment, first for standard and than for robust category. A comparison example of initial and final FRFs for R category in Z axis is shown in Fig.9 while Fig.10 shows very good matching of corresponding ultrasonic signals.

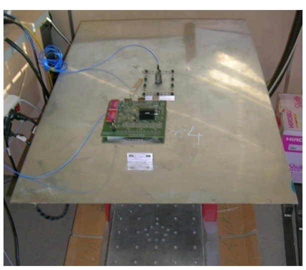

Fig. 7. Test set up in axis Z, Al specimen with PhA II & PAMELA III on shaker.

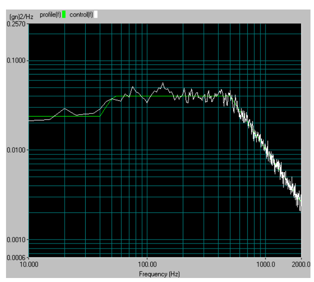

Fig. 8. Applied APSD in Z axis C1 curve Robust Random tests.

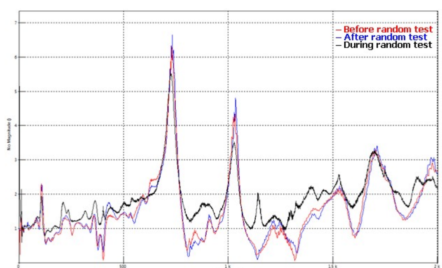

Fig. 9. Comparison of PhA II transducers FRF's before and after sine sweep & random robust vibration tests, Z axis.

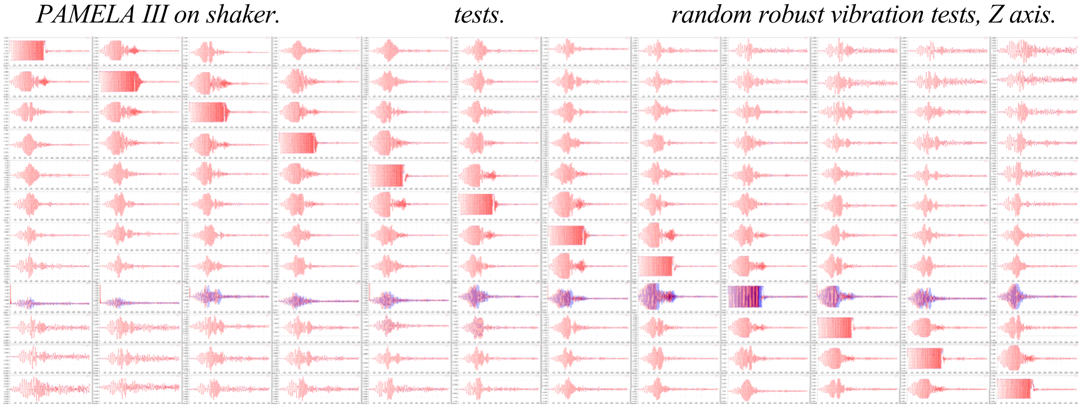

Fig. 10. Initial part of 12x12ultrasonic responses before(blue) and after(red) robust vibration tests.

Acquired ultrasonic structural responses without any signal cuts, signal breaks, sharp uncommon peaks or similar symptoms of signal integrity loss, distortion or signal quality loss imply that corresponding transducer is compliant with performance requirements within required specifications.

Thermal Loading (uniform temperatures)

Besides the resistance to static and dynamic mechanical loading, PhA II transducer performance compliance and resistance to thermal loading is of utmost importance for efficient and reliable SHM. Three types of thermal loading were performed on aluminum and CFRP specimens (with and without damage): (non)uniform thermal loading and thermal cycling, where for each new condition ultrasonic responses were acquired by different PAMELA SHM™ system test mode types and configurations of interest. The test set up and used climatic chamber are shown in Fig.11 and Fig.15.

Simultaneous ultrasonic responses were acquired on both panels, coupling two PhA II transducers with two PAMELA III devices by cable harness, for each temperature step (Fig.12, 13), fist cooling to -60C and then heating up to 150ºC. Once finished all signal acquisitions were checked in order to analyze that transducers and signal integrity on all channels is assured. An example of signal changes for several different temperatures shows the significant effect on resulting ultrasonic waves. It has to be emphasized that this amplitude and phase changes (Fig. 14) of ultrasonic waves are result of coupled temperature effects due to a combination of temperature sensitivities of host structure, transducer and adhesive.

Always when measuring something (ultrasonic waves in our case) it is of importance to completely understand the behavior and all environmental or performance dependencies of the measurement equipment for the entire envelope of possible service environments. These were also campaign test objectives herein.

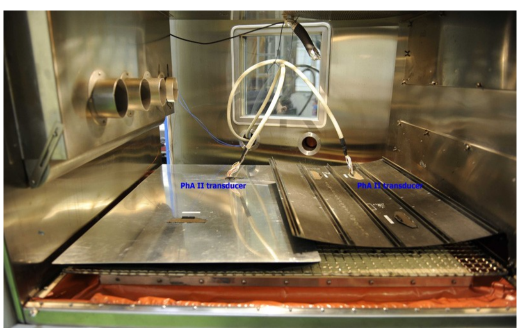

Fig. 11. AL & CFRP specimen in climatic chamber (PhA II bonded by different adhesives.

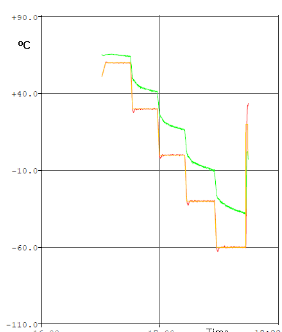

Fig. 12. Cooling steps down to -60ºC.

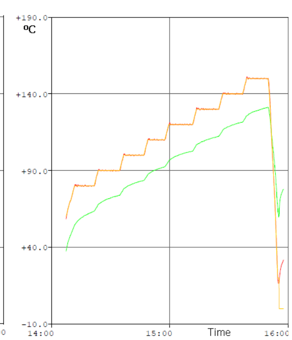

Fig. 13. Heating steps up to +150ºC.

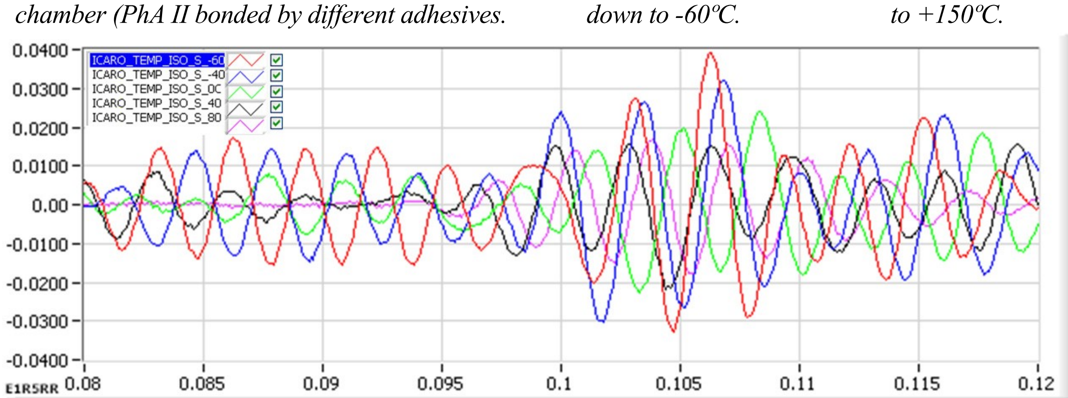

Fig. 14. Zoom of one of the response matrix elements for 5 different temperatures (Al specimen).

Thermal Cycling Loading

The principal objectives of thermal cycling loading tests were to asses and verify PhA II transducer resistance and survivability for very high temperature gradients, of importance for space applications, up to 35ºC/min during ten full cycles (Fig.16). Several acquisitions of ultrasonic responses were acquired before the tests and after that on maximum and minimum temperature for each thermal cycle. Adhesive resistance was also analyzed. These tests were also performed simultaneously on aluminum and CFRP specimen (Fig.11, 15). The proof of transducer resistance and its continued performance is shown on Fig. 17 where an example ultrasonic signal changes are compared on cycle nº5 between minimum and maximum temperature.

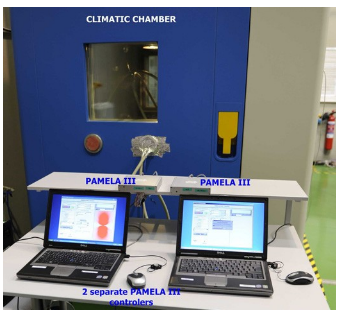

Fig. 15. Test set up with two separate PAMELA III controllers for SHM.

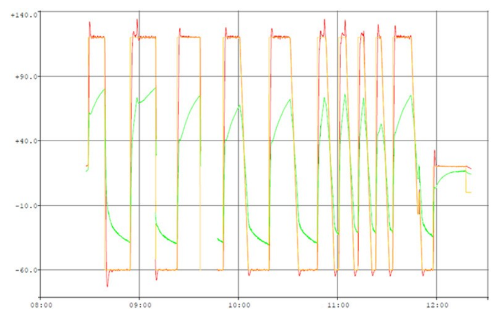

Fig. 16. Thermal cycling tests with 10 full temperature cycles applied (from -60C to +120C with 35ºC/min ramp).

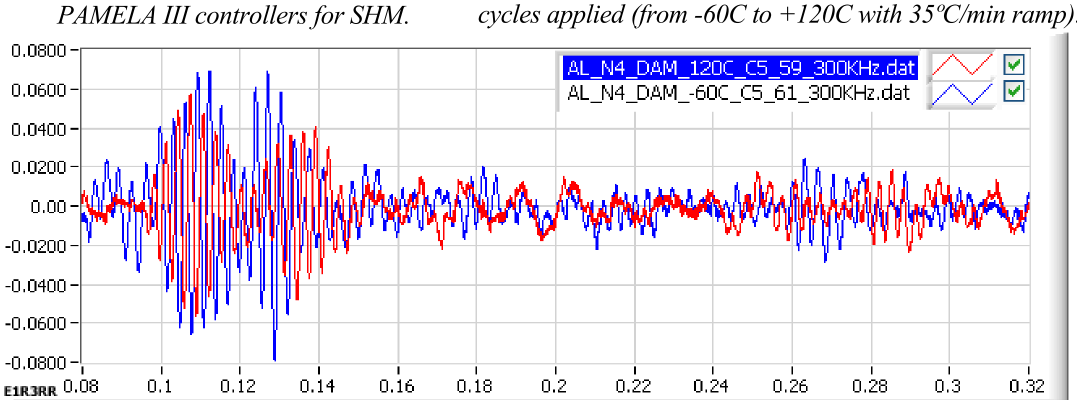

Fig. 17. Zoom of one of the response matrix elements,5th cycle with -60ºC and +120ºC (Al specimen).

Thermal Loading (non uniform temperatures)

The main reason to perform non uniform thermal loading tests was not due to transducer temperature resistance concerns but in order to acquire knowledge and understating of ultrasonic wave propagations when subjected to different temperature gradients and how these could affect resulting structural responses. These tests were performed on different aluminium and CFRP specimens (with and without damage) in free-free boundary condition by using a lamp as a heat source (Fig.18 -22). Specimens were heated by the lamp on three different positions (P1, P2, P3) and ultrasonic responses were acquired by PAMELA SHM™ system on each lamp position accordingly. Simultaneously, temperature distributions by thermographic camera were acquired in order to use temperature maps for posterior analysis and development of temperature distribution algorithms. An example of signal changes (mainly amplitudes) for three different heat source positions is shown in Fig.23.

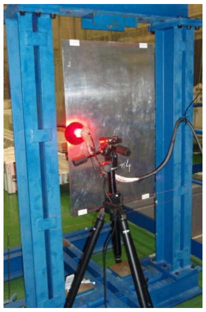

Fig.18. Heat source on P1(AL).

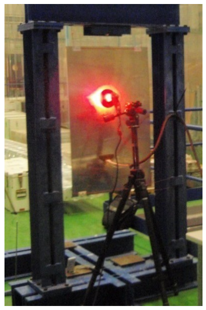

Fig.19. Heat source on P2(AL).

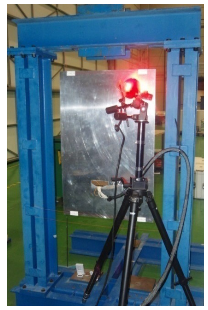

Fig.20. Heat source P3(AL).

Fig.21. Heat source P1(CFRP).

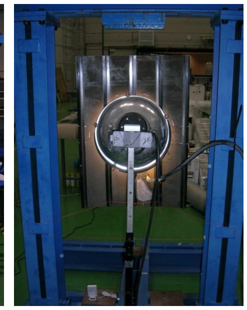

Fig.22. Heat source P2(CFRP).

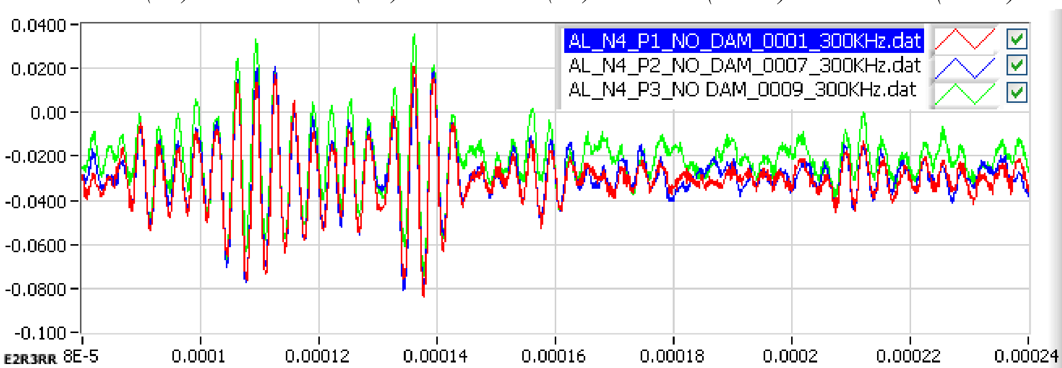

Fig. 23. Zoom of one of the response matrix elements for 3 different heat source positions (Al specimen).

It is important to mention (for proper assessment of signal quality in all tests) that no signal post processing tools like denoising, frequency filtering, attenuation corrections, curve fitting, signal deformation, etc. were applied on the ultrasonic responses presented on Fig. 6, 10, 14, 17 and 23. All test signals were acquired for duration of 10000-25000 samples, with 12.5MHz sampling frequency and by several PAMELA III test modes, like Fast Round Robin, Transmitter Beamforming, Transmitter Focusing, etc. [3],[4].

Other tests of importance and which were performed on/with PhA II transducers and PAMELA SHM™ system inside AERNNOVA's verification and validation tests were: impact resistance loading tests (near field), electromagnetic interference tests, combined thermo-mechanical loading tests, SHM tests during assembly of aerospace structure and SHM tests with structure subjected to electrical currents. These last tests, were ultrasonic waves were measured with PAMELA SHM™ system having the structure subjected to different electrical currents were the ones that most surprising results showed. The previously thought assumption that electrical currents in the structure do not produce effects on ultrasonic waves has been shown not to be true. Further research will be directed also in this direction, in order to obtain the knowledge and necessary understanding of ultrasonic wave propagation behavior in electrically loaded structures.

CONCLUSIONS AND RECOMMENDATIONS

Structural and signal integrity of developed PhA II transducer has been verified through an extensive V&V test campaigns and always installed on some host structure by different adhesives. A huge data base of ultrasonic structural responses (with very well documented all important tests conditions) has been acquired in order to analyze all kind of environmental influences on ultrasonic wave propagations (with resulting effects in different structures) which understanding is necessary in order to be able to always distinguish these effects from permanent structural changes due to all kind of potential damages that could occur in real service environments.

Through the test campaigns it has been shown that ultrasonic waves are very sensitive to all kind of influences (some of them not thought before) and have very high potential for SHM in the future taking into account their damage sensibility. PAMELA SHM™ system proved to be a very useful and powerful tool for all kind of SHM tests and also as a development platform of SHM algorithms for real aerospace structures. This is due to several important system characteristics, like for example easy transducer installation and associated PAMELA III devices directly above it on any kind of structure without need for cumbersome cabling (only 12DC power supply), autonomous system, low weight and low power, with flexible deployment characteristics, huge range of test modes and configuration possibilities.

Related with the temperature effects on ultrasonic responses it is recommended that separated thermal tests should be done in three steps, in the future, in order to be able to acquire complete knowledge and understanding of resulting temperature effects, first subjecting only the transducer, than transducer with the adhesive above and then finally panel with transducer bonded.

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