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Structural Health Monitoring Platform for Industrial Scale Composite Structures

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Abstract. Structural Health Monitoring technologies have been proposed in multiple research publications as a path forward to shift the current scheduled-based maintenance operations to a more physics-informed condition-based maintenance. The implementation of Structural Health Monitoring (SHM) technologies on aircraft components requires the development of a single platform able to perform the required signal acquisition and data storage for posterior post-processing. This manuscript outlines the further developments on a SHM data acquisition platform which enables monitoring environmental temperature variations with parallel performance of both active Guided Wave Structural Health Monitoring and Electromechanical Impedance analysis with sequential upload of the test's meta-data to an SQL database for posterior data processing and information safekeeping. The current platform was validated during the complete sensorization and damage detection on a large curved composite stiffened panel, representative an aircraft fuselage barrel section.

INTRODUCTION

In the aeronautical sector, full-field Structural Health Monitoring (SHM) technologies have been proposed for optimization of current maintenance procedures by switching from a scheduled-based to a condition-based approach [1], where physics-informed models draw the maintenance requirements by correlating the SHM model features with the structural degradation and the decrease in the material's yield strength allowing, therefore, higher flexibility in structural design.

Traditional full-field SHM techniques rely on Guided Wave propagation (GWSHM), Electromechanical Impedance Analysis (EMI) and Acoustic Emission (AE) for monitoring of both accessible and, particularly, inaccessible locations where classical NDT techniques fail. These SHM approaches take advantage of piezoelectric (PZT) sensor materials which convert electric potential differentials into mechanical vibrations from/into the structure. In the case of GWSHM, reliable approaches for damage detection rely on pristine methods where the sensor's response is compared between the two stages: a pristine one, where the signal response is known and corresponds to an undamaged structure and another where the material's state is unknown. Similar procedures can be employed when employing EMI methods for damage assessment [2]. In the case of AE techniques this falls into the passive SHM category where a sensor-external source generates the vibrations captured by signals. The signal sources are multiple, including impacts [3] and damage-related vibrations [4].

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GWSHM application in smaller structures such as small plate coupons can be easily conducted using single waveform generators and oscilloscopes for signal acquisition. However, upscaling these techniques to large-size structures representative of aircraft sections require larger networks to be employed due to their higher region of interests. In these cases, more elaborate and condensed systems are required due to the high number of actuator-sensor permutations in the sensor network.

Environmental and operational conditions (EOC) are of particular concern in vibration based SHM techniques due to their influence on the waves TOA and amplitude [5]. Particularly, for pristine methods if temperature effects are not fully compensated this can raise significantly the false positive rate, meaning damage is detected by the sensor network when the structure is not damaged [6].

Multiple concerns can be raised regarding future implementation of SHM techniques in aircraft structures, namely regarding the SHM system's reliability, durability and resilience to varying environmental and operational conditions, to the current separate data acquisition and processing systems for each available SHM technology. Particularly the latter, adds considerable weight on the structure which translates in discouraging dramatic increases on fuel consumption costs over the aircraft lifecycle. Hence, the need for a unifying SHM platform exists for increasing the reliability and encourage the adoption of these techniques during aircraft manufacturing. In addition, the reliability of the SHM hardware (sensors, wires, bonding) must be separated from the reliability of the SHM data (noise, attenuation, environmental and operational conditions). Therefore, the SHM system proposed during this work has high reliability and redundancy through the application of the diagnostic film [7] which is repairable/replaceable and by having self-diagnostic capabilities through EMI measurement. The EMI measurement has been demonstrated to be a reliable method for integrity assessment of the sensor and their installation [8]. The only disadvantage is current off-the-shelf acquisition for recording the EMI response is separated from the typical wave generator and oscilloscope solutions that are used for guided wave measurement. This increases the complexity of the hardware as well as the software for an automated data base recording of large industrial structures. Though not specific to SHM, governmental agencies like NASA [9-11] have also highlighted the need for a unique platform in health assurance systems reinforcing this requirement for the future introduction of SHM techniques in aircraft manufacturing.

EMI-SHM systems for signal acquisition with frequencies between 20kHz and 30kHz have been integrated into a Raspberry Pi 3 module [12] aided by a multiplexer for switching between different piezoelectric sensor with NoSQL database measurement storage. Moreover, Ma et al. [13] have successfully proposed the development an SHM LabVIEW code for GW and EMI signal acquisition using similar hardware as the one employed during this work. The authors validated this approach using 6 bonded PZT disks to an Aluminium plate and performing damage assessment by increasing the system's mass.

During the large-scale FP7 European Project named ‘‘Smart Intelligent Aircraft Structures —SARISTU’’ in 2015 a SHM platform [14] was developed for the experimental testing of a composite wingbox. The test campaign comprised the bonding of 160 piezoelectric sensors surrounding locations prone to damage generation during the mechanical tests. The damages were successfully detected and localized using traditional imaging algorithms [15].

A data efficient SHM platform [16] (LASAR) for GW acquisition was performed for the experimental campaign of the SHM Building Block's levels during the SHERLOC project [5, 17] part of the CleanSky 2 Joint Initiative. This platform was validated by performing damage detection of Barely Visible Impact damages on a flat composite stiffened panel [8]. This platform constitutes the initial design for the current developed platform.

The main aim of this paper is to present a unified solution for data acquisition and processing of industrial scale structures, with high reliability and quality of the recorded data. This platform will be the basis for the SHM assessment of the structure through its service life. This solution will be accomplished by enhancing the capabilities of an in-house developed SHM platform solely developed for GW signal acquisition. This new platform allows for the acquisition of both Guided Waves and EMI signals of an expanded number of input channels by performing the necessary changes to the software and expanding the existing hardware. Moreover, the platform can measure EOC changes during signal acquisition by running parallel temperature measurements to the on-going acquisition task. An SQL database uploading feature was also included in the platform for the test metadata for posterior information access such as date, sensor location and type of actuation signal: chirp, toneburst, among others. Further on-going developments for the acquisition platform include passive acquisition of signals from the sensor network for AE events and damage growth monitoring during the structural degradation. The enhanced platform is validated through GWSHM measurements on a curved composite stiffened panel, representative of an aircraft fuselage barrel section at different temperatures using the new platform features.

DEVELOPMENT OF AN ENHANCED STRUCTURAL HEALTH MONITORING PLATFORM

The selection for the current SHM platform architecture required extensive research regarding current available technologies which could address the necessary requirements both from a hardware and a software perspective. A detailed list of these requirements can be found in [16]. After the down-selection process for the platform technology the obtained solution relied on a selection of National Instruments (NI) hardware systems, comprised of computer programmed oscilloscopes and waveform generators which provided the adequate actuation and acquisition properties whilst enabling easy expansion of further input channels provided the adequate additional multiplexer hardware are included [18] and the required changes to the software are considered.

Hardware

The current DAQ hardware for the experimental campaign consisted in a PXI Chassis with an Arbitrary waveform generator card (NI-5412), one oscilloscope card (NI-5105) and two 12 × 8 RF Matrix switch (Pickering 40-726A-511-L). This setup allowed acquisition of signals from a maximum of 24 sensors, corresponding to the amount of input channels supplied by the multiplexer matrix. The current oscilloscope hardware solution supplies an acquisition frequency of 60MHz, given the current high frequency bandwidth of the actuation/receiving signals [6] the Nyquist–Shannon sampling theorem requirements are fulfilled. The proposed DAQ hardware assembly was managed using a NI-8802 controller, the 16GB RAM memory supplied by the controller proved to successfully handle the data storage memory requirements from the software platform.

Environmental and Operational Monitoring

Current GWSHM studies usually rely on laboratorial controlled environments where no significant temperature changes occur that introduce significant changes on vibration propagation which compromise the efficiency of damage detection algorithms. However, during application of GWSHM technologies during aircraft component testing the environment conditions will be substantially different. Here, EOC effects may occur in various formats however, vibration and temperature changes are the most common. Though vibrations during the acquisition phase can influence the signals response, such effects can be circumvented by introducing appropriate filter technology [19] and increasing the number of acquisition signals with subsequent averaging. Temperature variations, however, introduce significant amplitude and phase changes in the wave propagation limiting the efficiency of damage detection algorithms unless these effects are compensated. Hence, in order to compensate temperature variations between signal acquisitions and avoid false positive alerts the SHM platform should also integrate a temperature quantification technology in parallel to the signal acquisition step.

The temperature acquisition hardware comprised of four NI 9122 cards connected to a NI cDAQ-9185 instrument was selected for performing this task given the easier integration to the software platform. The temperature hardware was connected to the NI controller through an Ethernet cable which enabled data collection from up-to 16 thermocouples (RS PRO Type K Thermocouple) with a maximum of +250°C.

A parallel temperature control menu was added to the platform and allows the user to select the type and number of thermocouples incorporated for temperature measurements. **FIGURE 1** illustrates the temperature acquisition menu with the input controls on the top right. The instantaneous temperatures are output into the right-side cluster and the temperature history is plotted on the left-side chart.

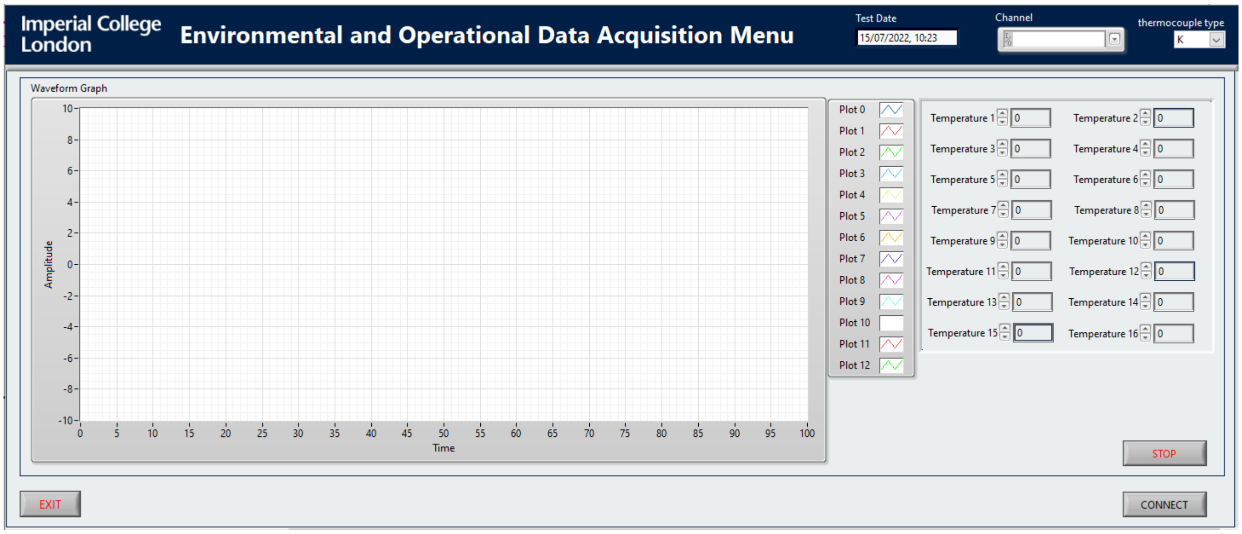

FIGURE 1. Temperature measurement platform LabVIEW menu

Electromechanical Impedance Analysis

Electromechanical Impedance Analysis correlates the structural mechanical impedance from a bonded PZT by measuring the electrical impedance of sensor. The frequency dependent electrical impedance $Z(\omega)$ can be written as the inverse of the electrical admittance $Y(\omega) = 1/Z(\omega)$ which relates to the PZT's mechanical properties through [20],

$$Y(\omega) = i\omega a\left[\bar{\varepsilon}_{33}^{T} - \frac{Z_S(\omega)}{Z_S(\omega) + Z_a(\omega)} d_{3x}^2 \hat{Y}_{xx}^{E}\right] \tag{1}$$

where $Z_a(\omega)$ corresponds to the sensors' mechanical impedance, $Z_S(\omega)$ is the host structure's mechanical impedance, ω is the angular frequency velocity, a is the geometry constant of the PZT, $\hat{Y}_{xx}^{E}$ is the complex Young's modulus of the PZT with zero electric field, d_{3x} is the piezoelectric strain constant in the arbitrary x direction at zero stress, $\bar{\varepsilon}_{33}^{T}$is the PZT dielectric constant at zero stress.

Calculation of each PZT sensor's, i, electrical impedance, $Z_{i,PZT}$, requires computing the frequency response functions (FRF), $H_{i0}(\omega)$, through the ratio between the discrete Fourier transform (DFT) of each sensor's response, X_i and the actuation signal input by the waveform generator X_0.

$$H_{i0}(\omega) = \frac{X_i(\omega)}{X_0(\omega)}, \qquad i = 1, \dots, n_T \tag{2}$$

where n_T is the total number of sensors present in the sensor network.

The FRF response of the PZT, is correlated to its electrical impedance, $Z_{i,PZT}$, by,

$$Z_{i,PZT}[\omega] = \frac{H_{i0}[\omega] Z_{in}[\omega] R_s}{Z_{in}[k] - H_{i0}[k](R_S + Z_{in}[\omega])} \tag{3}$$

where Z_{in} is the internal impedance of the acquisition hardware computed using the NI card's internal specifications, and $R_S$the internal calibration resistance.

Finally, the electrical admittance of the PZT, $Y_i(\omega)$, is given by the inverse of the electrical impedance, $Z_{i,PZT}(\omega)$, and the admittance components, Conductance and Susceptance, correspond, respectively, to the real and imaginary parts of $Y_i(\omega)$.

Current EMI-SHM tasks rely on the usage of commercial high-resolution systems [21, 22], however, most of these systems are bulky and/or single input, hence, require continuous connection switches by the user for inspection of the whole sensor network making it laboriously demanding, time consuming and increases the chance for connection damages. Particularly in such networks, these shortcomings render the whole SHM system unappealing. Again, here the need for the development of a fast and user efficient platform is highlighted when considering SHM in large structures with many sensors.

In the platform proposed here, the software, acquisition methodology, saving operation, and hardware proposed for GW acquisition was employed for performing the separate EMI analysis for the sensor's bondline integrity assessment. The EMI measurements were performed by changing a single wire in the switch matrix and conducting GW pulse-echo measurements on the sensor network with a chirp actuation signal. The postprocessing analysis was restricted to the measurements' first sections. However, the current measurements required that one of the input channels remained disconnected to any PZT sensor since the response of this channel corresponded to the actuation signal transmitted to each PZT senso. The chirp actuation signal was applied considering an initial frequency $f_0 = 10\text{kHz}$ and final frequency of $f_1 = 600\text{kHz}$. The analytical expression for such signal is given by,

$$V(t) = V[H(t) - H(t-T)]\, sin\left(2\pi\left[f_0 t + \frac{f_1 - f_0}{2T}t^2\right]\right), \tag{4}$$

where $H(\cdot)$ is the Heaviside function, t the time array, and T is the chirp signal duration, here considered as 200μs.

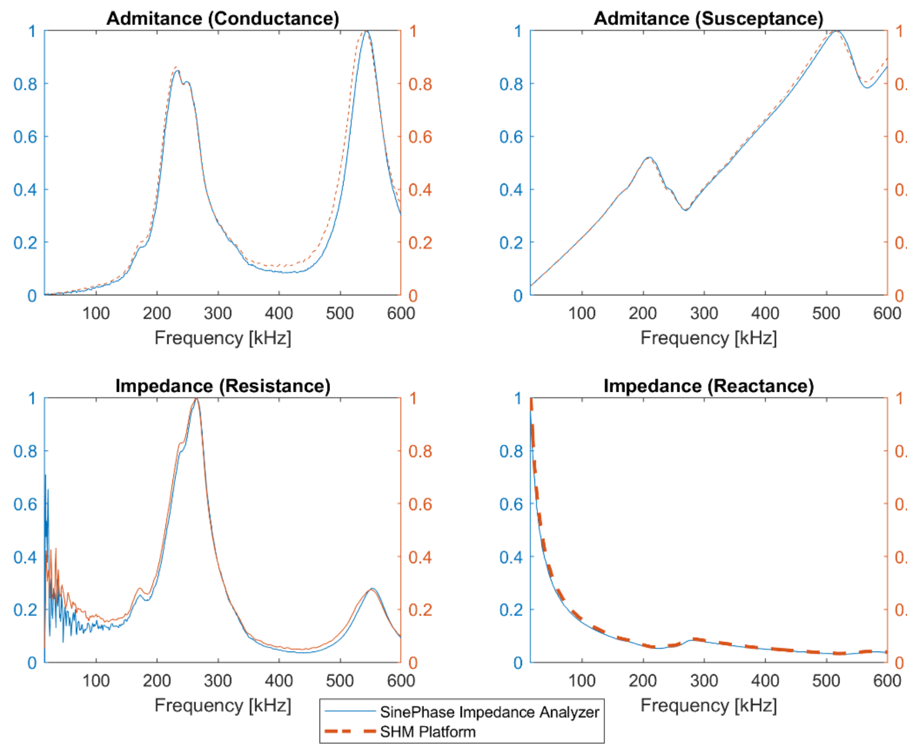

FIGURE 2. EMI analysis performed on a bonded sensor to a CFRP coupon with a commercial technology and the developed SHM platform

Figure 2 illustrates the non-dimensional difference between the EMI measurement's outputs obtained using a standard commercial device, Sinephase Impedance Analyzer 16777k [21], and the measurement obtained from the current SHM system. The overall components from the EMI analysis show a good agreement between both systems particularly at lower frequencies, at higher frequencies slight differences occur particularly for the Admittance components.

SQL database metadata import

The expansion of the previous SHM platform [16] envisioned its application for full GWSHM on large aircraft structures. In these conditions, until a self-diagnosis framework is proposed, the signal acquisition and signal postprocessing may not be performed by the same individual. Hence, an information link must exist between the two parties in order to optimize the maintenance approach and prevent loss of information which may compromise the aircraft's operation safety.

Here, an SQL database is proposed to address the aforementioned condition. The database is incorporated in the SHM platform to store each test's metadata at the user's request. The uploaded information includes test parameters such as the acquisition time, name, the specimen type (Coupon, Monostringer, Curved Panel), the sensor location and origin, and additional information regarding the actuation signal. The GW signals were chosen not to be included in this database given the large size of each measurement compilation (all sequential measurements considered) which would render the database unusable. For this, a on-site cloud storage upload would be more efficient.

The uploading operation was programmed in the LabVIEW environment using the library provided by James David Powell's (SQLite Library).

Acquisition Software

The software environment chosen for controlling the DAQ hardware was LabVIEW given the dedicated environment supplied for data acquisition operations and the numerous libraries and functions available with the user license.

The large number of sensors present in the structure required a specific acquisition algorithm to be established in order to perform the pitch catch measurements effectively. Hence, an expanded version of an in-house LabView code [16] was developed to generate the necessary excitation for Guided wave generation. This platform enabled the acquisition of the same maximum number of sensors as supported by the Hardware system and is easily expanded provided additional switch matrices are connected and the accordingly RAM memory improvements. **FIGURE *3*** illustrates the user interface of the expanded LASAR platform [16].

FIGURE 3. Expanded SHM Platform user interface.

SHM PLATFORM EXPERIMENTAL VALIDATION

During this work the SHM framework is established in a 5-meter-long curved composite stiffened panel representative of a regional aircraft fuselage barrel section. The radius of this panel is 1.67m and reinforced longitudinally by CFRP stringers and transversely Aluminium frames. The stacking sequence for the panel's skin and for the longitudinal stringers are $[\pm 45/0_2/90/0]_s$, each with a thickness of 2.208mm. The panel was designed by the SI&HM group at Imperial College London, manufacturing was performed by FIDAMC.

Diagnostic film development and sensor bonding

The curved stiffened panel was extensively sensorized using an in-house designed diagnostic film relying on the inkjet printing of two silver tracks using a Dimatix DMP-2850 Printer. The tracks were printed using a nanoparticle silver ink (Sigma-Aldrich 791903-10G) in a 60µm Kapton film with a drop spacing of 6.9 µm. To increase the electrical conductivity, each track was sequentially printed 3 times and sintered at 135ºC. The piezoelectric sensors (DuraAct, PI Ceramic) were attached to the tracks using a 1:1 conductive Epoxy (RS Pro Liquid Adhesive) and cured at 85 ºC. The diagnostic film had been extensively tested for real-life operational conditions [7] and no detrimental effect was detected in comparison with the original structure as well as the applicability for SHM in flat stiffened composite structures [8]. **FIGURE *4*** shows the diagnostic film developed at Imperial College London and used to sensorized the stiffened panel.

FIGURE 4. Diagnostic Film used for sensorization of the curved stiffened panel

The stiffened panel was sensorized using 72 piezoelectric sensors and the bonding of the diagnostic films to the curved panel was done through curing of a thermoplastic film [23] using an Anita Hot Bonder Console (GMI Aero) and vacuum bagging around the stiffeners where a pump exerted the required load to attach the sensors.

Finally, bond monitoring of the full sensor network was performed through an Electromechanical Impedance (EMI) analysis using the proposed SHM platform and is illustrated in **FIGURE *5***.

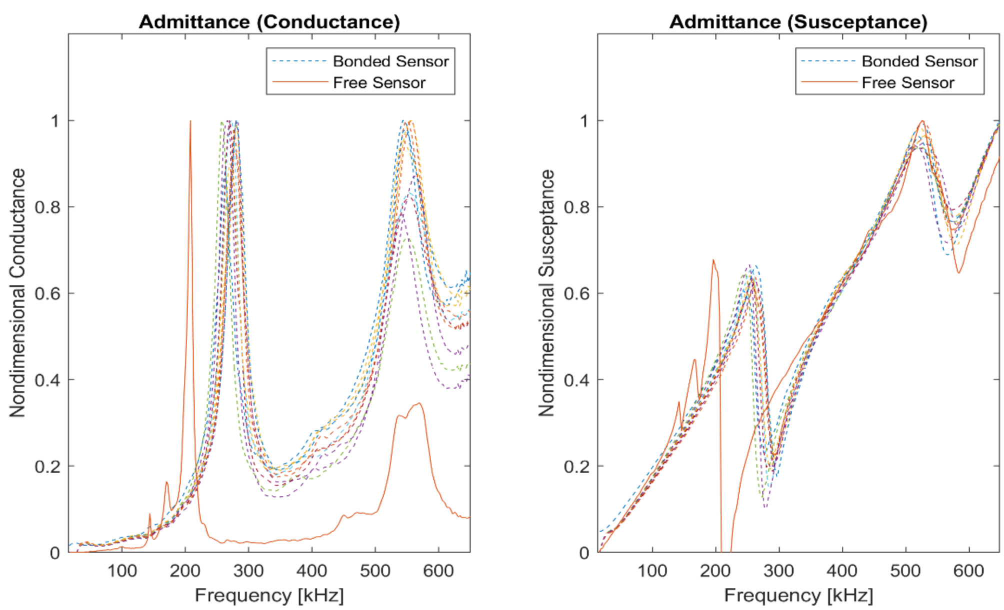

FIGURE 5. EMI analysis of 12 bonded PZT sensors from the curved panel using the proposed SHM platform

Analysis of **FIGURE *5*** shows the variability on the Admittance components from the EMI analysis performed on 12 PZT sensors bonded on the curved panel and a measurement performed on a free PZT. Closer inspection of both the Conductance and Susceptance first peak shows a shift on frequency peak, from around 200 kHz to around 250-300 kHz. This shift in frequency indicates to the user that the sensor is bonded to the structure [2, 8].

Actuation Signal generation

Guided wave excitation was generated through a chirp actuation signal with the same parameters as performed in the EMI measurements, given in equation (4). The sensor network tested considered in each acquisition comprised of 16 PZT sensors, illustrated in **FIGURE *6***.

During each acquisition operation, 10 consecutive measurements were taken for each actuator-sensor pair to improve the experiment's signal-to-noise ratio and consecutively the signals were averaged. Posteriorly, the individual Lamb Wave modes' central frequency individual Toneburst response were deconvoluted from the chirp signal's sensor response [24]. Specifically, 50kHz for the A0 wave mode and 250kHz for the S0 mode as to the material's dispersion curves.

Signal Acquisition

The reliability of the proposed SHM system will be directly related to the detection capabilities at different locations in the structure. Simultaneously, the exponential attenuation associated to the propagation of guided waves in structures [25] must be taken into consideration when selecting the actuator-sensor paths under inspection. Moreover, temperature compensation factors have been computed [26] for specific distance and attenuation profiles for an 8-sensor network which will render ineffective for larger paths. Therefore, in the postprocessing step of the analysis, the 16-sensor acquisition network was divided into three subnetworks where the GW signals were inspected. **FIGURE *6*** illustrates the acquisition network and the respective three analysis subnetworks.

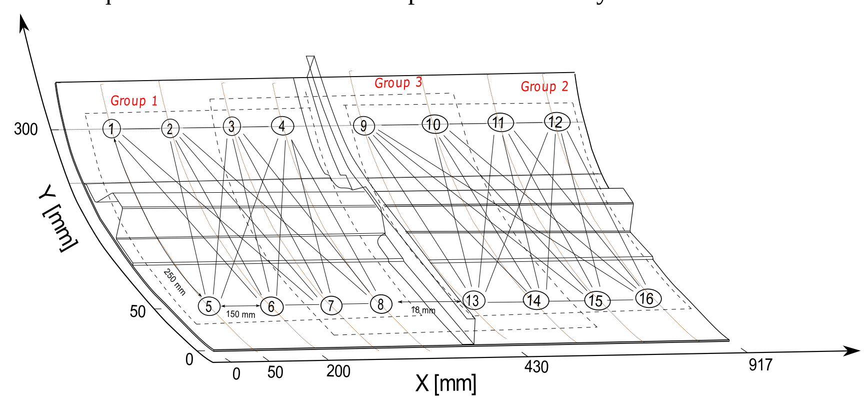

FIGURE 6. Sensor grouping for each of the curved panel's acquisition grouping.

Following the acquisition group sensor numbering in **FIGURE *6***, the signal response from the actuation from equation (4) were reconstructed for each actuator and sensor pair and are represented in **FIGURE *7*** . These correspond to signals from two different grouping subnetworks but acquired simultaneously which further highlighting time saving features from the platform. Moreover, the attenuation effect from the longitudinal stringer is evident by the amplitude decrease on both symmetric and antisymmetric wave modes.

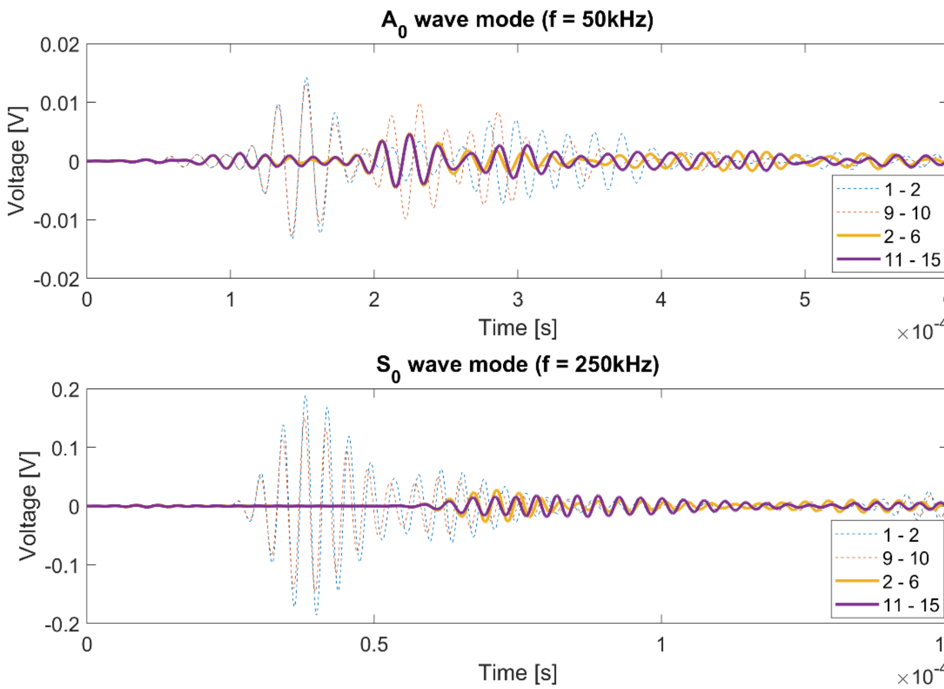

FIGURE 7. Signals reconstructed for two different wave modes for four different actuator-sensor pairs

The full integration of the platform for SHM operations is represented in Figure 8 where all 24 channels are connected to the rows of sensors and GW signals from one of the sensors can be seen on the software interface.

FIGURE 8. Integration of the SHM platform for signal acquisition in the curved stiffened panel

CONCLUSION

In this work the improvements to an existing SHM platform have been outlined for performing both GWSHM and EMI measurements on large sensor network. The hardware selected for this platform provides sufficient actuation and acquisition properties for the high-frequency excitation of guided waves in multiple structures. Moreover, the technology employed allows for further expansion of this system by performing the necessary hardware extensions (extra multiplexer matrices) and simple software modifications.

The current system has been validated by employing it for signal acquisition on a large, curved composite stiffened panel with diagnostic PZT films surface-mounted on the panel's skin. The sensor network was divided into numerous 16-sensor subnetworks to accommodate the platform channel properties.

The expansion of this system also accommodated the capability to perform sensor bondline integrity assessment through EMI measurements by using the same technology for GWSHM through pulse-echo measurements and provided fivefold operational time savings to the classical single input available technologies where the user is required to perform multiple repetitive connection switches.

This platform delivers a further step into the implementation of SHM technologies for damage assessment in aircraft structures by addressing concerns regarding the need for a multitude of acquisition and processing software allowing the operator to take full advantage of multiple SHM technologies for damage detection and integrity assessment.

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