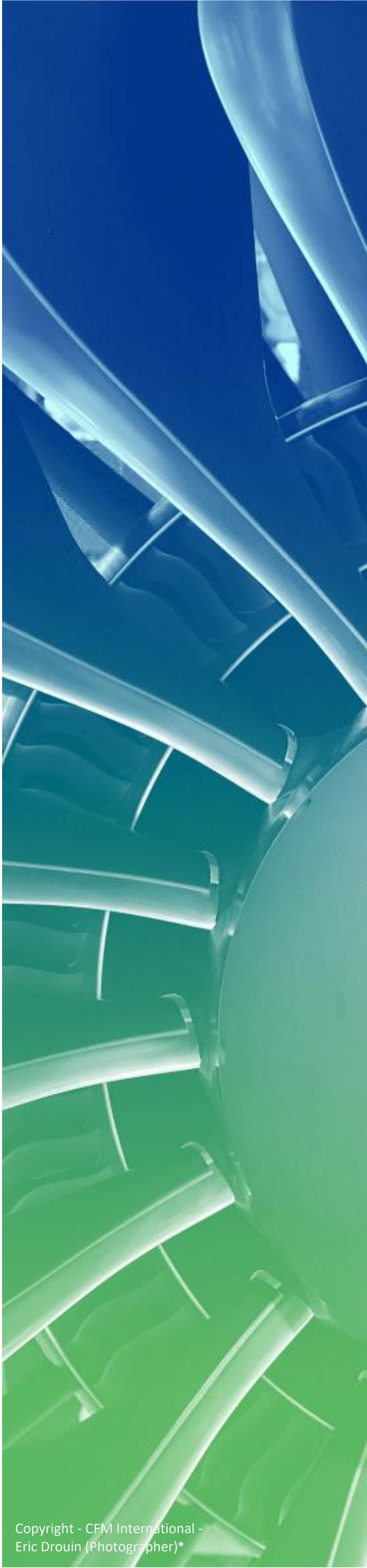
An experimental data set for the SHM of a substructure of an engine fan blade



Embedded Life-Cycle Management for Smart Multimaterials Structures: Application to Engine Components

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An experimental data set for the SHM of a substructure of an engine fan blade

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Keywords

Structural Health Monitoring (SHM), Aircraft Engine Blades, Curved Panel, 3D-woven Composite, Hybrid Metal-Composite, 4-point Bending, Fatigue Testing, FBG Sensors, Guided Waves, PZT Transducers.

Abstract

This article presents a dataset collected during an experimental campaign run within the H2020 – MORPHO project on a Foreign Object Damage(FOD) panel, which is a representative substructure of a LEAP engine fan blade. This FOD panel is manufactured from a 3D-woven composite, has a steel leading edge on one side, and measures approximately 800 mm and 350 mm in length and width, respectively. This FOD panel is additionally curved with varying cross-sectional thickness along its width.

In terms of transducers, this FOD panel is equipped with newly developed screen printed piezoelectric transducers (PZTs) and optical Fiber Bragg Grating strain sensors (FBGs). Printed PZTs are positioned in five arrays (four close to the corners and one at the centre) with five printed PZTs each. Four standard ceramic PZTs are also bonded to the panel. Two optical fibres with each eight FBGs each are also adhesively bonded at the bottom side of the panel. After one impact damage, the FOD panel is subjected to fatigue multi-cycles 4-point bending tests with increased load severity until failure of the panel. The FBGs are used to continuously measure the strains during the bending tests. Ultrasonic guided wave measurements are performed periodically on the FOD panel using PZTs in order to acquire data at various stages of degradation of the panel between the healthy and failed states. The four standard PZTs are used to excite tone burst signals at 30, 50, 60, 90, 100, 150, 200 and 250 kHz individually and all the standard and printed PZTs are used to acquire the signals. Ultrasonic measurements are repeated ten times for each actuator and excitation frequency. The load-displacement data from the bending tests (as measured by the hydraulic machine) are also measured. This dataset additionally contains the impact response of the FOD panel as measured by the PZTs and the electromechanical impedances of the printed PZTs measured before and after failure.

This dataset thus offers unique insight into i) ultrasonic guided wave propagation into curved and varying thickness composite structures, ii) the use of innovative screen printed PZTs for SHM purposes, iii) the complementarity between FBGs and PZTs for SHM purposes and finally iv) it can be used as a training dataset and a benchmark for prognosis algorithms.

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1. VALUE OF THE DATA

• This dataset offers unique insight into ultrasonic guided wave propagation into curved and varying thickness composite structures representative of the aeronautic industry. Available public data are usually limited to flat and uniform rectangular plate or to geometrically complex aeronautic structures. The FOD is thus an interesting structure laying between both extremes.

• This dataset can promote the use of innovative printed PZTs that have been used for the first time here for SHM purposes. These transducers are lightweight and can printed of any arbitrary shape. Available experimental data provided within the dataset can thus allow to model them and to assess their sensitivity and dynamic response.

• FBGs and PZTs are two promising candidate technologies for the SHM of aeronautic composite structures. However existing datasets are usually targeting only one of those technologies and rarely both. As here synchronous experimental measurements for both technologies are available in the present dataset, it can allow researchers to assess the complementarity between FBGs and PZTs for SHM purposes and to better delineate their respective advantages and drawbacks.

• Prognosis algorithms aim at providing estimates of the remaining useful life of engineering structures and needs data to be trained and benchmarked. The proposed dataset constitutes an interesting case study in such a context and can thus be used for prognosis purposes.

2. BACKGROUND

Structural Health Monitoring (SHM) can provide information to reduce downtimes and costs associated with inspections and maintenance by allowing to detect, localize, quantify, and follow damage propagation (Lima, Perrone, Carboni, & Bernasconi, 2021; Sharif Khodaei & Aliabadi, 2016; Marques, Unel, Yildiz, & Suleman, 2019). An underrepresented aspect in SHM literature is the structural reliability of aircraft engines. Composite engine blades still remain vulnerable to impact damage, which greatly compromise operational safety by creating subsurface damages that can significantly reduce the structure's load bearing capabilities (Dorey, 1984; Azouaoui, Azari, & Pluvinage, 2010). The FOD panel is a substructure of the LEAP engine fan blade. It is a highly complex curved structure build up with state of the art 3D woven carbon fiber composite body. A sensor network is the first stage towards successful SHM (Abbas, Li, & Qiu, 2018). The screen printing technology is being leveraged in this work to fabricate arrays of piezoelectric transducers that have negligible weight, can be easily removed, and are very promising for ultrasonic based SHM. Furthermore, Fiber Bragg Gratings appears as another very interesting sensing technology for strain based SHM. During the generation of this dataset, a simpler quasistatic but closer to realistic operational fatigue loading scheme is employed to mimic operating, damage initiation, and damage growth conditions in the FOD panel while sensors data are being collected in-situ.

3. DATA DESCRIPTION

3.1. Overview

The MORPHO data are organized within one single HDF5 format file grouping all the collected data and called "*MORPHO_FOD7.h5*". An overview of the content of this HDF5 file is provided in Figure 1. HDF5 files are extremely useful data containers that can be organized internally as *Groups* with some *Attributes* that corresponds to the metadata associated with each group and that can contain either other groups or data in the form of *Datasets*. The HDF5 file format has been chosen here as it is an Open Source Format that can be read by many scientific computing languages (such as *Matlab* and *Python* to cite only a few) and for which many information and example codes are publicly made available (https://www.hdfgroup.org/, s.d.).

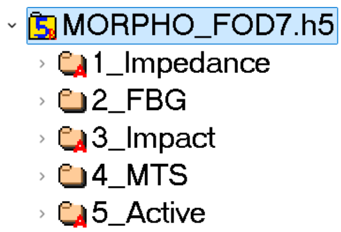


Figure 1: Overview of the "MORPHO_FOD7.h5" file organization

Within the HDF5 file provided in the dataset, the data corresponding to each sensing technology are organized as explained in the following subsections and each correspond to a given group. The main advantage of this data container technology is that a selected dataset within the architecture can be loaded without loading the whole dataset which speeds up access and limits memory needs. Furthermore, packaging all the data in a single container which is not a compressed folder largely ease its practical use as no compressing and uncompressing operations are required. In order to help future users of this dataset, a *Matlab* code is providing examples to load and plot data of each type. This code is denoted "*EXAMPLE_READ_DATA.m*" and is made available along with the dataset in the repository.

3.2. Impedance data

The **impedance data** are stored in the group called "*1_Impedance*". Impedance corresponds to the ratio between the imposed voltage and the resulting current in a given PZT at a given frequency. Impedance measurements are available for the **healthy state** of the FOD, for the **damaged state** after the impact and all the fatigue load states. Two groups correspond to those two states, namely "*FOD7_Healthy*" and "*FOD7_Failed*". Within these group, there are **groups for each printed PZT** for which impedance data are available that a denoted as "PZT_*N*" with *N* ranging from 5 to 29. No impedance measurements have been carried out for standard ceramic PZTs numbered from 1 to 4. Within one PZT group, 3 datasets in the form of 1D matrices are available: the first one Z provides the modulus of the impedance (in Ω), the second one *phase* provides the phase (in °) of the impedance and the last one *freq* the corresponding frequencies (in Hz). Measurements have been carried out on 801 frequency points. Start frequency, stop frequency, number of measurement points, and voltage level are provided as attributes in the "*1_Impedance*".group.

An overview of the "*1_Impedance*"group using *HDFView* software is shown in Figure 2[Left]. The various groups detailed previously along with the corresponding data can be seen on that figure. An example of impedance signals is shown in Figure 2 [Right].

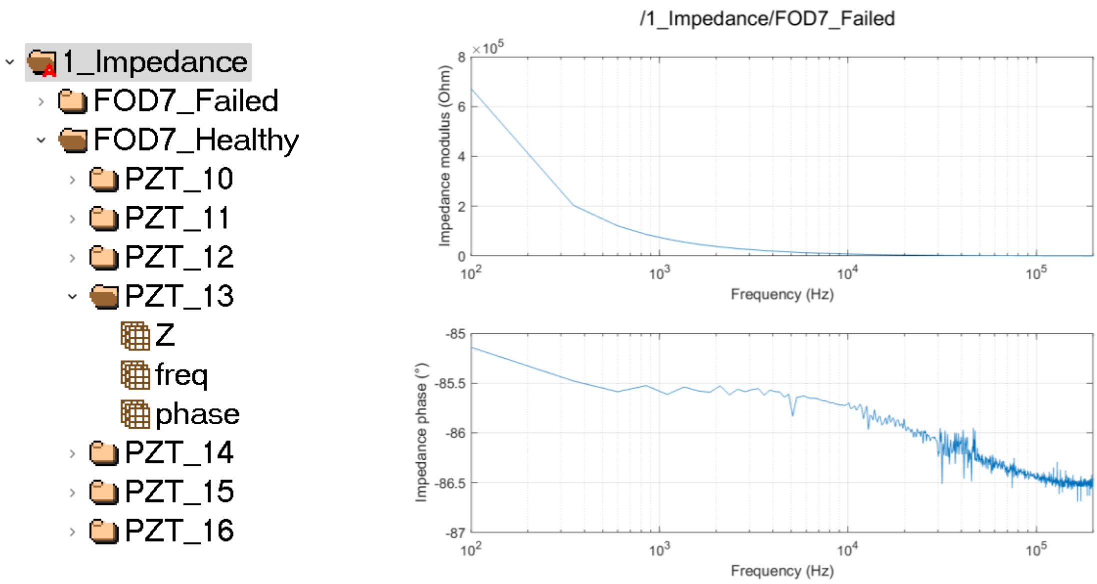


Figure 2: [Left] HDF5 file organization of one experiment for impedance measurements. [Right] Snapshot of impedance data contained within the database.

3.3. Fiber Bragg Gratings data

The **Fiber Bragg Gratings** (FBG) **data** are stored in the group called "2_*FBG*". Within this group, groups corresponding to a **given load** X after N cycles are available as "XkN_N". Loads X of 4, 8, 12, 16, 18, 20, 22, and 24 kN are available. FBG data for cycles N of 200 and 400 are available for loads smaller than 20 kN and for cycles N of 100, 200, 300 and 400 for larger loads. Within these group, there are **groups for each FBG** denoted as "FBG_N" with N ranging from 1 to 16. Within one FBG group, 2 datasets in the form of 1D matrices are available: the first one *FBG_data* provides the strain measured by this FBG (in µm/mm) over time, the second one *time* provides the associated time values (in s).

An overview of the "*2_FBG*"group using *HDFView* software is shown in Figure 3[Left]. The various Groups detailed previously along with the corresponding data can be seen on that Figure. An example of FBG signals is shown in Figure 3[Right].

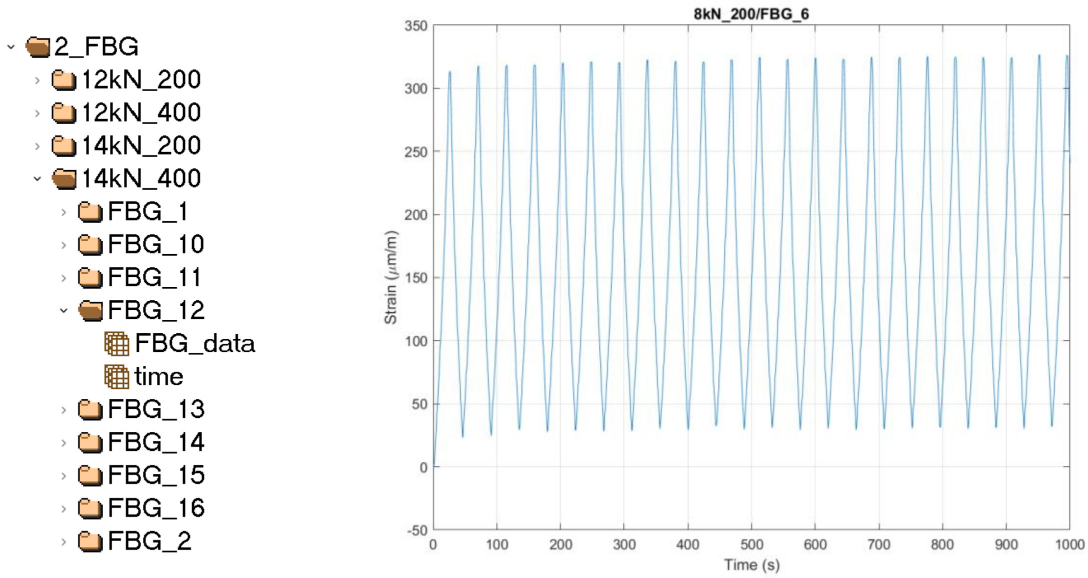


Figure 3: [Left] HDF5 file organization of one experiment for FBG measurements. [Right] Snapshot of FBG data contained within the database.

3.4. Impact data

The **impact data** are stored in a group called "*3_Impact*". Within this group, there are **groups for each PZT** denoted as "PZT_*N*" with *N* ranging from 1 to 29. Within each PZT group, a dataset denoted *PZT_data* is available. This dataset corresponds to a time series of the recording achieved by this PZT element during the impact event. The sampling frequency is stored as an attribute of the "*3_Impact*" group.

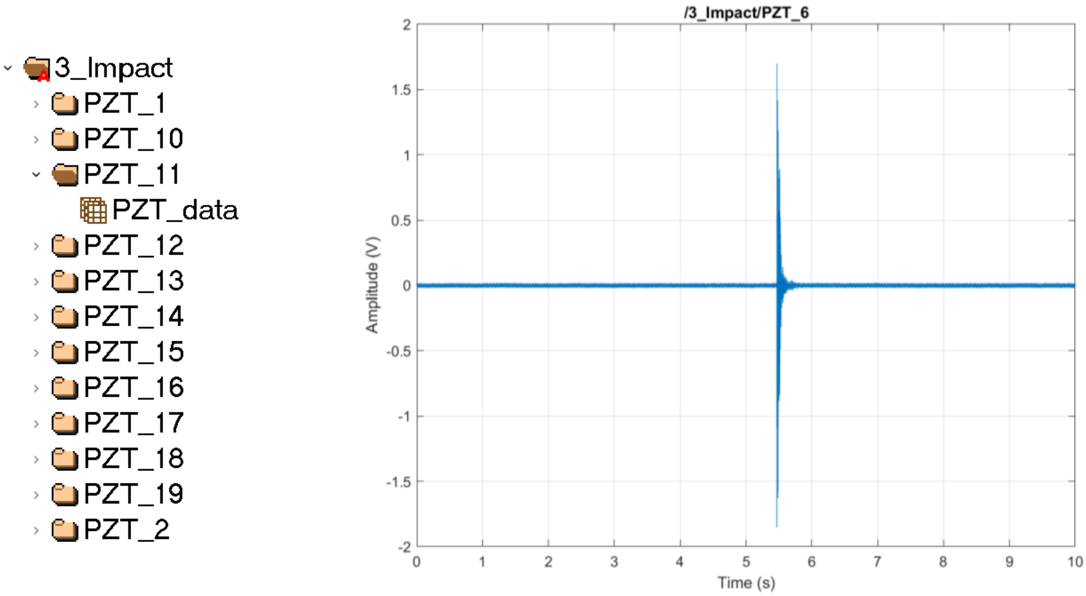


Figure 4: [Left] HDF5 file organization of one experiment for impact measurements. [Right] Snapshot of impact data contained within the database.

An overview of the *"3_Impact"*group using *HDFView* software is shown in Figure 4[Left]. The various groups detailed previously along with the corresponding data can be seen on that figure. An example of impact signal is shown in Figure 4[Right].

3.5. MTS data

The data recorded by the **MTS machine** are stored in a group called "*4_MTS*". Within this group, groups corresponding to a **given load** X after N cycles are available as "XkN_N". Loads X of 4, 8, 12, 16, 18, 20, 22, and 24 kN are available. MTS data for cycles N of 200 and 400 are available for loads smaller than 20 kN and for cycles N of 100, 200, 300 and 400 for larger loads. Within these groups, 3 datasets in the form of 1D matrices are available: the first one *displacement* provides the displacement in mm measured by the MTS machine over time, the second one *load* provides the force in kN measured by the MTS machine over time, the last one *time* provides the associated time values.

An overview of the *"4_MTS"*group using *HDFView* software is shown in Figure 5[Left]. The various groups detailed previously along with the corresponding data can be seen on that figure. An example of MTS machine signals is shown in Figure 5[Right].

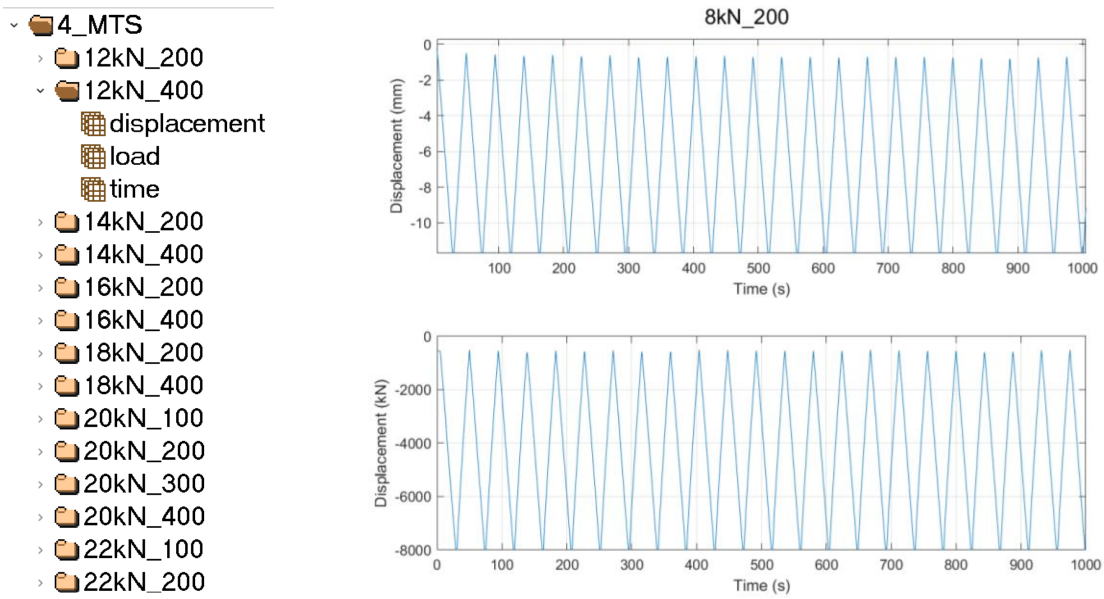


Figure 5: [Left] HDF5 file organization of one experiment for MTS measurements. [Right] Snapshot of MTS data contained within the database.

3.6. Ultrasonic Lamb waves data

The data corresponding to ultrasonic Lamb waves sent an received by standard or printed piezoelectric transducers (PZTs) are stored in the group called "*5_Active*". Standard PZTs are numbered from 1 to 4 and printed PZTs from 5 to 29. An attribute called "*PZT_info_geo*" provides the geometrical positions (x, y) of the 4 PZTs bonded on the plate expressed in m.

Each subgroup within this group corresponds to a given **Lamb waves data at a given damage state** of the FOD panel. Groups corresponding to the healthy FOD panel either clamped or unclamped are available (namely "*Healthy_Clamped*" and "*Healthy_Unclamped*") and can be used as a baseline. Groups corresponding to the FOD panel after the impact occurs, either clamped or unclamped are also available (namely "*AfterImpact_Clamped*" and "*AfterImpact_Unclamped*") and can be used as alternate baseline or for impact monitoring purposes. Finally groups corresponding to a given load X after N cycles are available as "XkN_N". Loads X of 4, 8, 12, 16, 18, 20, 22, and 24 kN are available. Ultrasonic interrogation for cycles N of 200 and 400 are available for loads smaller than 20 kN and for cycles N of 100, 200, 300 and 400 for larger loads.

Within each of these damage case groups, groups denoted "*FkHz_5cycles*" are dedicated to specify the **burst test signal** that has been used (here a 5 cycles tone burst with a frequency of F kHz) with F being either 30, 50, 60, 90, 100, 150, 200 or 250 kHz. Attributes attached to this group are the sampling frequency (1 MHz), the central frequency (F in kHz), the number of cycles (5 cycles) and the name of the signal (Burst FkHz 5 cycles).

Within each burst test signal group, one group is attributed to **each actuator**. This group is named "*ActionneurK*" with K the actuator number ranging between 1 and 4 as only the 4 standard ceramic PZTs where used as actuators in the present experiment. No specific attributes are attached to the "*ActionneurK*" groups. These groups then finally contain the data as a dataset denoted "*measured_data_rep_L.mat*" with L corresponding to the repetition number and ranging between 1 and 10. These data are stored in the form of 2D matrices with one dimension corresponding to discrete time and the other dimension organized as follows: time value, actuation signal, and measured signals. For example, if the emitting transducer is the PZT number 3, this second dimension is organized as: time value, signal sent to PZT 3, and signals measured by PZTs 1, 2, 4, 5 up to 29.

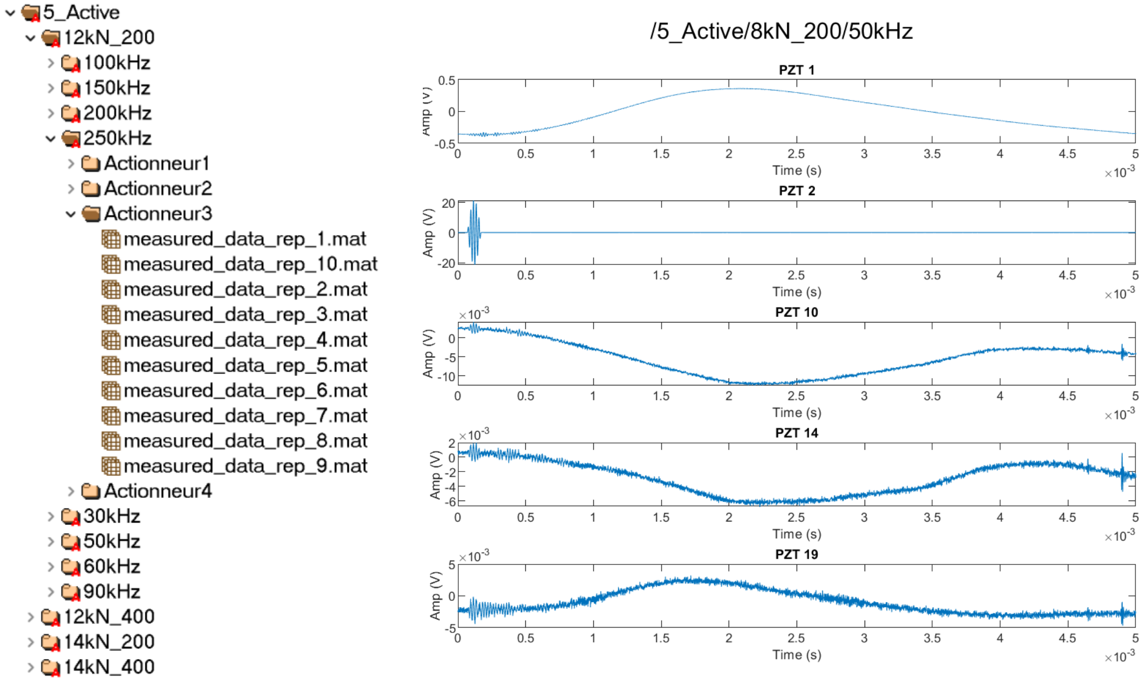


Figure 6: [Left] HDF5 file organization of one experiment for ultrasonic Lamb waves measurements. [Right] Snapshot of data contained within the database.

An overview of the "*5_Active*" group using *HDFView* software is shown in Figure 6 [Left]. The various Groups detailed previously along with the corresponding data can be seen on that Figure. An example of ultrasonic Lamb waves signals is shown in Figure 6 [Right] when PZT 2 is used as an actuator.

4. EXPERIMENTAL METHODS

4.1. EXPERIMENTAL STRUCTURE & MATERIAL

The FOD panel used in these experiments possesses a curved 3D-woven carbon fibre composite body with a nominal length of 800 mm and a width of 350 mm. It is manufactured by resin transfer molding by SAFRAN Composites. The FOD panel is completed by a secondary bonded metallic leading edge, with a width of 50 mm, adhered to one of the lengthwise edges. The cross-sectional thickness of the FOD panel is variable, with the leading (including the steel edge) and trailing edge having a thickness of 6.3 mm and 2.8 mm, respectively, and the mid-section thickness measures approximately 10.8 mm. The full FOD panel with the steel leading edge and transducers is shown in Figure 7(a), while Figure 7(b) shows the curved nature of the panel along with the variation in its cross-sectional thickness.

(a) FOD panel with printed piezoelectric transducers (b) Side

Figure 7: FOD panel used in the experiments

Two sensors systems are employed to monitor the FOD panel, which are fibre optic sensors in the form of fibre Bragg grating (FBG) sensors, and two types of piezoelectric transducers, namely standard ceramic disc transducers and screen printed transducers. The overall dimensions of the panel along with the locations of all the piezoelectric transducers and FBG sensors is shown in Figure 8(a) and (b).

4.2. Impact test

At first, an impact test is performed on the FOD panel to introduce a barely visible impact damage using a drop tower apparatus. The FOD panel is clamped at the edges, while sandbags are placed underneath to eliminate the elastic deformation during the impact and allow the panel to absorb most of the impact energy. The weight and diameter of the spherical impactor is 5 kg and 10 mm, respectively, and the impact energy is approximately 55 J. All the four ceramic transducers along with the 25 printed transducers are connected to 32 channeled HBM Nicolet data acquisition system. HBM Perception data acquisition software is used to record the impact signals with an acquisition frequency of 1 MHz. The order in which the data is stored based on sensor numbering is shown in Figure 8(c).

4.3. Fatigue tests experimental design

The FOD panel is tested on a MTS 810 hydraulic machine using a 100 kN load cell under a 4-point bending load scheme, where the support and loading pin locations are selected according to ASTM D7264/D7264M – 07 standard. A 6 mm radius was selected for the four pins after a preliminary finite element analysis showed highest failure load compared to the other investigated radii of 12 and 15 mm. This selection was guided only by the highest failure load criterion. This loading scheme is selected to simulate close to realistic operational loads whilst evaluating the flexural stress-strain response before and after internal damage has occurred and/ or external damage is introduced.

The 4-point bending test followed an increased severity loading scheme starting at 4 kN and increasing until failure of the FOD panel as shown in Table 1. Each load is applied for 400 cycles, in a displacement controlled scheme with a linear load-hold-unload format. The load blocks are divided into subblocks, where the load blocks are interrupted every 200 until 18 kN and 100 cycles from 20 kN to perform for ultrasonic Lamb waves measurements, where the panels are kept at -0.5 kN. These periodic measurements provide guided waves measurements at various degradation state of the FOD panel. Consequently, the subblocks are named as "*4kN_200*" for first 200 cycles of 4 kN load block, "*4kN_400*" for cycles 201 to 400 of 4 kN load block, and so on. These subblocks are also used to refer to the degradation states of the FOD panel.

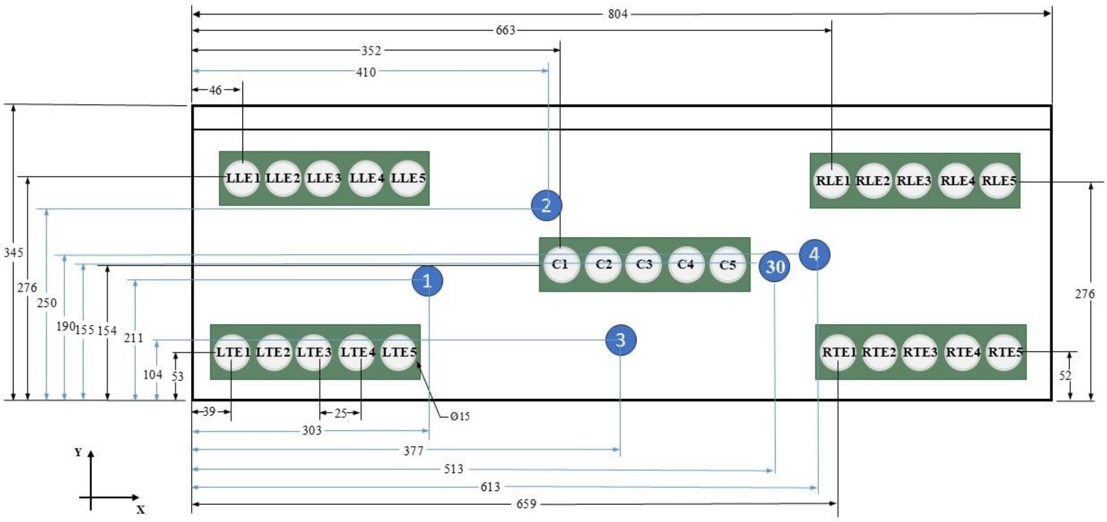
Block No.	*Load in kN*	*Guided wave interval*
1	*4*	*200*
2	*8*	*200*
3	*12*	*200*
4	*14*	*200*
5	*16*	*200*
6	*18*	*200*
7	*20*	*100*
8	*22*	*100*
9	*24*	*100*

Table 1: Load blocks used for 4-point bending test

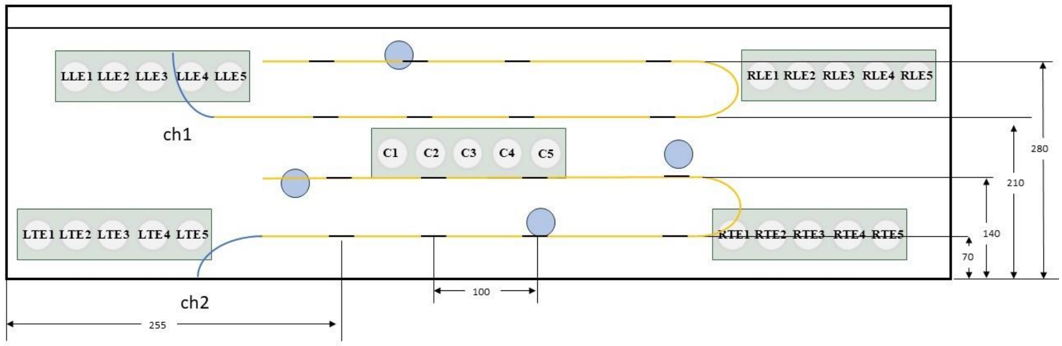
The load-displacement profiles for all the cycles at each load block are collected from the MTS 810. A laser displacement sensor is also integrated with the MTS to measure the displacement at one point in the middle of the FOD panel.

4.4. FBG sensors experimental setup

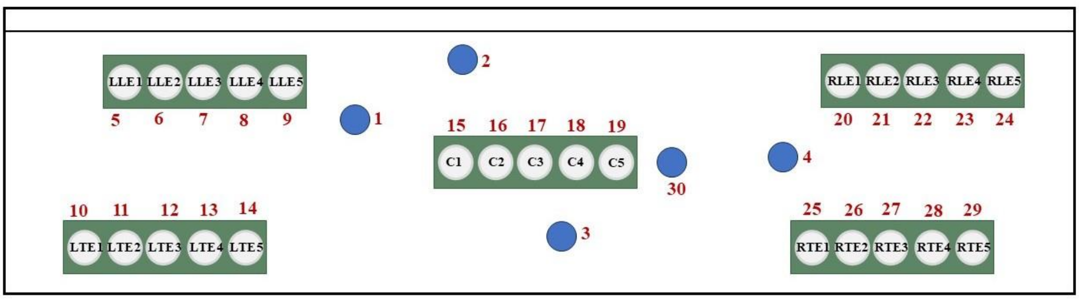
Two optical fibres (FiSens FBG sensor array 850 nm) with 8 FBGs each are adhesively bonded at the bottom side of the panel using an instantaneous strain gauge adhesive cured at room temperature. It is ensured that the location of the optical fibers is in between the support pins, where the deformation is largest, while along the width, three locations are preferred, i.e., close to the trailing edge, close to the leading edge, and at the center of the panel. Thus, in total 16 FBGs in two optical fibers are located in 4 lines across the width of the panel, as shown in Figure 8(b). The optical fibres are connected to a 4-channelled FiSpec FBG X400 Interrogator. The FBGs are used to measure the strain data using the FiSens FBG-Interrogator 3.1 data acquisition software at an acquisition rate of 1 Hz. The strain data are measured during the entirety of each block. The strain values are zeroed before every new (sub)block is run because it was observed that the residual strains negatively affect the subsequent measurements.



(a) Dimensions of the panel and locations of the piezoelectric transducers



(b) Locations of the FBGs



(c) Numbering used for piezoelectric transducers while storing the data

Figure 8: Locations of various sensors and numbering used for data storage

4.5. PZTs transducers experimental setup

The FOD panel houses two types of piezoelectric transducers, namely , standard ceramic disc type transducers and novel screen printed transducers. The state of the art screen printing technology is employed for the first time to print piezoelectric sensors on the FOD panel after manufacturing in the H2020 – MORPHO project. These printed PZT sensors have a diameter of 15 mm and thickness of approximately 135 µm and are being employed for measuring ultrasonic guided waves propagation in the panel. The printed PZTs are printed in five arrays of five sensors each located close to the four corners of the FOD panel and at the center of the FOD panels, for a total of 25 printed transducers on one FOD panel. Along with those 25 printed transducers, four ceramic disc type transducers are bonded using acrylic glue around the middle portion of the FOD panel such that the four ceramic transducers form the nodes of an imaginary quadrilateral. The location of the all the piezoelectric transducers is shown in Figure 8(a).

For the ultrasonic guided wave measurements, the FOD panel is kept stationed between the pins at a barely loaded state and measurements are performed at the end of each (sub)block as shown in Table 1: Load blocks used for 4-point bending test. In total, tone burst signals of eight central frequencies – 30, 50, 60, 90, 100, 150, 200, and 250 kHz - are excited using the four ceramic transducers as actuators individually in a serial manner. All the four ceramic transducers along with the 25 printed transducers are connected to 32 channeled HBM Nicolet data acquisition system, and HBM Perception data acquisition software is used to record the signals. A total of 10 repetitions of the measurements are performed for each actuator with a sampling rate of 1 MHz, yielding a total of 40 measurements per frequency for each sensor. The order in which the data is stored based on sensor numbering is shown in Figure 8(c). Please note that the Sensor 4 broke during the impact test, and a replacement Sensor 30 was bonded close to the location of the Sensor 4 after the impact test. This Sensor 30 is then connected instead of Sensor 4 and used for measurements in place of Sensor 4.

5. LIMITATIONS

Limitations associated with the present dataset are the following ones:

- The sophisticated industrial and expensive manufacturing process of the FOD panel limit the availability of large numbers of panels for generation of such a dataset. Replicating such a dataset may thus be extremely hard in practice which makes it unique and thus probably difficult to compare to other ones.
- The printed piezoelectric transducers are still nascent and under development and it is to be acknowledge whether or not they provide reliable measurements for ultrasonic guided waves measurement purposes. Indeed, these printed piezoelectric transducers generate a low voltage output, resulting in a limited signal-to-noise ratio. Hence, the consistency and reliability of the guided waves signals measured by the printed piezoelectric transducers must be assessed.
- The optical fibres are bonded on the bottom side of the FOD panel, and the strains measured by the FBG sensors on these optical fibres will be different from the strains on the top or centre of the panel. Also, local damage located outside the FBG sensor range will not affect the local strain field around the sensors hence there will be difficulty identifying the presence of damage.
- The experiments comprise of cyclic quasistatic loading, which is complex yet simpler than actual fatigue, particularly so in regard to random load fatigue failure observed in complex industrial structures.
- The exact time of impact is not known as the impact test was performed using a drop impact tower.

6. ACKNOWLEDGEMENTS

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