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Proof of concept for impact and flaw detection in airborne structures

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Abstract

All structures are subject to unwanted and uncontrolled bumps. For instance, when considering airborne vehicles, birds, hail, and meteors are usual sources of collision. Depending on the location and energy of the impacts, they can weaken the structure critically. On the other hand, ageing, scratching, corrosion, and manufacturing flaws also weaken structures. Furthermore, the subsequent damage could not be visible, as it usually happens in composite material made structures. This paper focuses on the detection of impacts and flaws of structures in airborne vehicles with an electronic prototype developed specifically for SHM (Structural Health Monitoring). Two types of tests were performed, the ones to detect impacts, and those to detect flaws. Both are based on the propagation of ultrasound acoustic waves. The setup of the tests includes the structure under test, a set of transducers, a structural health monitoring ultrasound system (SHMUS), and the software to control the monitoring tool. The first type of tests are based on the Impact Detection System (IDS) included in SHMUS. Any impact on the structure under test generates an acoustic wave that IDS detects. The parameters of the waveform generated depend on the energy that the impact provides. The second type of tests, the flaw detection tests, are performed with SHMUS, which generates and acquires electric signals, and simplify them for further analysis and health diagnosis of the structure. Once an impact is detected, it is critical to know the degree of damage caused to the structure. To this end, SHMUS can perform an SHM test, the second type one. The results show that the monitoring system SHMUS satisfactorily detects impacts and flaws as well as measures the damage as a decrease of the health of the structure under test. Furthermore, the decrease detected is proportional to the severity of the damage.

Keywords: Impact detection; Damage detection; SHM;

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1. Introduction

Unwanted and uncontrolled bumps may happen to any structure. As an example, when considering airborne vehicles, those bumps can be due to birds, hail, and meteors. Impacts can weaken any structure critically, depending on the location, speed, and energy of the impacts, Safri et al. (2014). Other phenomena, as ageing, scratching, corrosion, and manufacturing flaws, can also weaken structures severely. Additionally, the subsequent damage could be invisible, as it usually happens in composite made structures. In addition, the cost of visual maintenance inspection, which is not negligible, sometimes could be just a waste of time and money. For many years, a research on setting Non Destructive testing (NDT) techniques is being carried out. The aim is to apply these techniques along an aircraft lifespan, according to Structural Health Monitoring (SHM) techniques by Güemes et al. (2020).

Literature reports many laboratory researches on impact and/or flaw detection in metal and composite specimens, Capineri and Bulleti (2021). They include instrumentation such as general-purpose I/O-data acquisition systems or oscilloscopes, which usually are limited in size, weight, and number of channels to take measurement. The size of equipment and accessibility for the structure integrity testing are not major issues when dealing with large and heavy structures, as the civil ones. However, when the structures to monitor are smaller and lighter, such factors turn to be relevant. For instance, the integrity inspection on airborne vehicles requires reliable low volume lightweight electronic equipment with high technical capability, Sharif-Khodaei et al. (2013). Most of the publications regarding this topic are focused on particular cases, with certain impact sources, over laboratory-oriented structures (simple geometry thin plates), with suitable sensors and algorithms that only seek foreseeable damage (Engholm and Stepinski (2011), Kwon et al. (2020), for example). This research focuses on damage determination of a structure that suffers from various types of harm. Two types of harm are considered: time-based damage like corrosion or delamination, and those due to an abrupt event such as an impact or similar. This paper summarizes the test campaign to gather signals and the analysis techniques considered.

2. SHM setup

The setup of the tests (figure 1) includes the structure under test, a set of transducers or Piezoelectric Wafer Active Sensors (PWAS Transducers) (Giurgiutiu (2007)), an electronic SHM Ultrasound System (SHMUS) by Etxaniz et al. (2021), and the software to control the monitoring tool. Some PWAS attached to the structure transform the electric signals into acoustic waves and vice versa. Acoustic waves propagate along the material and they change with any new imperfection inside the structure due to some damage.

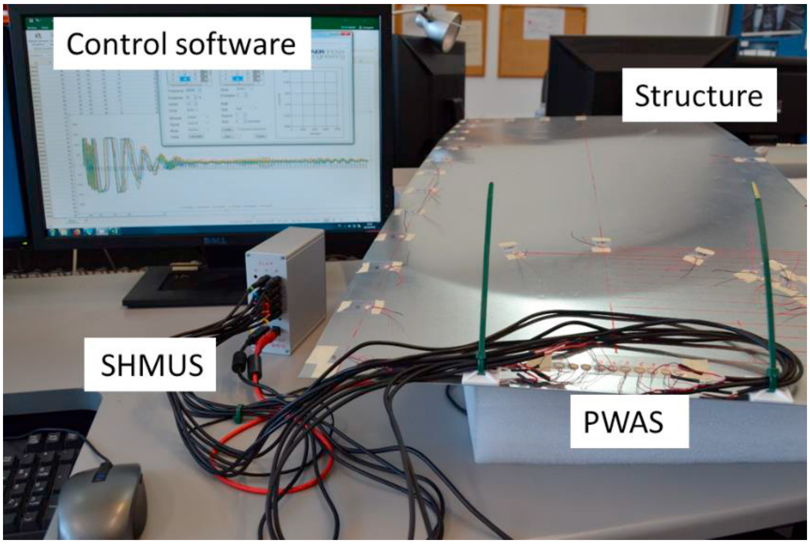

Fig. 1. Setup for the SHM test.

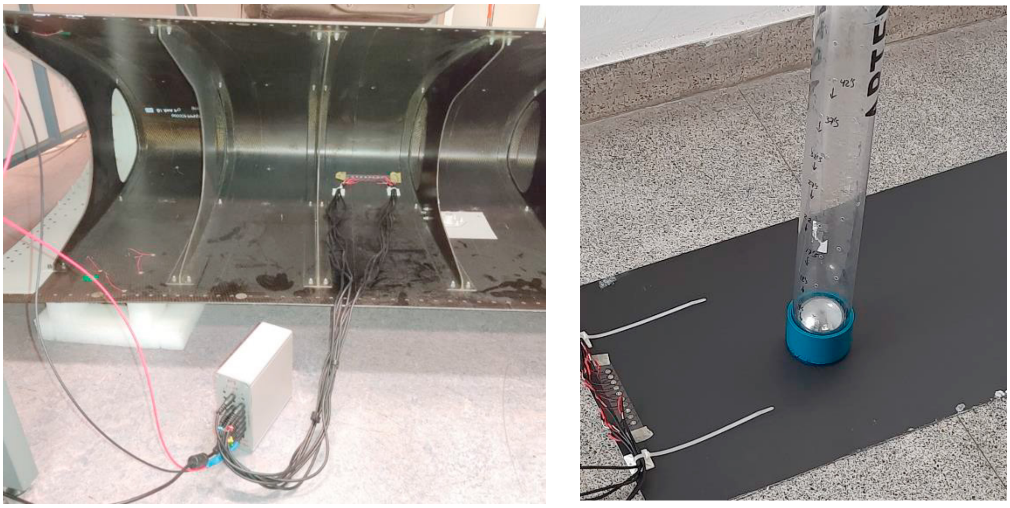

Fig. 2. (a) Leading edge under test, and (b) system used to emulate the real-world impacts.

The tests are carried out on two type of materials, carbon-fiber reinforced polymer (CFRP) and aluminum. They show different properties for the propagation of ultrasound waves. The tests are carried out on two type of structures, some of them were square plates, and the other was a real-world leading edge (figure 2 a). The leading edge was built by Aernnova, which is a well-known metal and composite airborne structure provider.

Two types of tests are considered, the ones to detect impacts, and those to detect flaws. Both are based on the propagation of ultrasound acoustic waves.

3. Impact Detection

The first type of tests is based on the Impact Detection System (IDS) included in SHMUS. Any impact on the structure under test generates an acoustic wave that IDS must detect. The parameters of the waveform generated depend on the energy that the impact provides. As shown, two elements were necessary to emulate the energy of an actual impact: a 600 grams steel ball and a tube with a set of holes at different heights (figure 2 b). If the mass and the height from which an object is thrown is known, the impact energy and object velocity can be calculated:

$$E_p = mgh \qquad [1]$$

On the other hand, the kinetic energy is obtained with the following formula:

$$E_c = \frac{1}{2} m V^2 \qquad [2]$$

The impact velocity can be calculated if we consider that the kinetic energy is equal to potential energy at the impact point.

$$V = \sqrt{\frac{2E_c}{m}} = \sqrt{\frac{2E_p}{m}} = \sqrt{2gh} \qquad [3]$$

The ball was chosen due to its shape, it has no edges and the same amount of pressure will be applied in every test, no matter if the object rotates. Finally, an SHMUS is connected to the PWAS and laptop.

Then, the passive mode is selected in the control software interface to listen to acoustic emissions. Additionally, one of the channels of SHMUS is also read by a general-purpose oscilloscope to compare the data gathered by SHMUS with the one measured by the oscilloscope. Thus, the precision and accuracy of the impact detection system can be analyzed.

First of all, IDS was tested on two plates, one made of isotropic material, and the other one made of anisotropic material, i.e. aluminum and CFRP. Each plate has an array of PWAS located close to the edge of each plate. The goal of these tests is to compare the data read from the sensors when applying the same energy at the same distance from the sensors.

Then, the tests on a real-world leading edge were carried out. Similarly, an array of PWAS was located on the part of the structure with the highest impact probability. The nearest to the impact point the array is, the less attenuated the signals are. As we did in the plates, an oscilloscope measured the signal provided by one of the transducers to compare the signal attenuation with different instrumentation. A leading edge of any plane is a complex geometry structure. It is not thin, flat, or square. It is hard to model. Such kind of structures attenuate ultrasound waves much more than thin plates do. The goal of the tests on the leading edge is to determine the sensitivity of SHMUS to detect impact, i.e. the minimum impact energy necessary, the location of the PWAS, the effect of the curve shape of the structure, etc. As expected, after the impacts, the leading edge is not apparently harmed.

4. Damage detection

The second type of tests requires not only the acquisition of signals, as IDS does, but also the generation of ultrasound waves to apply them to the structure under test. SHMUS carries out such actions. Additionally, SHMUS preprocesses the amount of acquired data to simplify any further analysis and health diagnosis of the structure. Once SHMUS detects an impact, it is critical to know the degree of damage caused to the structure. The damage detection in each structure was performed following two types of tests:

- Round Robin. One channel emits an ultrasound wave and the echoes are acquired in all the channels of SHMUS.
- Beamforming. When the right delay is applied to each PWAS in the array, constructive interference happens in a certain direction and then an ultrasound beam is steered to that direction [8]. Again, the echoes are acquired in all the channels of SHMUS.

The damage detection tests to analyze the performance of the guided waves through the structures were carried out on a daily basis for two months. Some stages were defined for these tests.

- The first stage analyzed the effects of progressive damage,
- The second one analyzed the consequences of several types of sudden damage.

The initial state was set in the first days, when no harm was applied to the structure and the effects of temperature showed up. Then, during 40 days, the corrosion conditions were emulated. Hypertonic saline water (2.2% salt concentration) was added, and the aluminum and composite structures were joined. Moreover, the room temperature was also measured every day. Next, the structures were separated. During a week, the room temperature was measured and the state of the structure was set as its new initial state.

Eventually, a series of sudden damage were applied to the structures. Then, tests were carried out to measure the integrity of the structure. The set of sudden damage applied to the structures consisted of multiple impacts, awl scratching, and several diameter drilling. Several rest days were taken after each damage application.

After the acquisition of signals, there are several approaches to analyze them.

The first one consists of obtaining the degree of health matrix (DoH) according to the algorithm explained by Cantero-Chinchilla el al. (2021). Figure 3 shows the evolution of the DoH matrix measured after each day of the stage 1 and after each sudden damage of the stage 2. It only shows 6 DoH matrices, which were obtained in the tests performed every 15 days. When the DoH matrix is greenish, the coefficients close are to “1”, and the health and integrity of the structure is almost the same as the one taken as reference.

As long as the health of the structure decreases, the coefficients of the matrix turn to be darker and closer to “0”. The tests demonstrate that the health of the structure decreases with time. Note that the DoH matrix does not depend on the type of damage considered. It determines the general health state of the structure, not the local damage nor the source of the health degradation.

a											b									
0.96	0.91	0.94	0.99	0.99	0.99	0.95	0.99	0.87	0.97		0.86	0.90	0.94	0.96	0.95	0.94	0.93	0.93	0.96	0.93
1.00	0.92	1.00	0.91	1.00	0.96	0.95	0.93	0.94	0.79		0.92	0.97	0.92	0.90	0.95	0.88	0.94	1.00	0.94	0.95
0.98	0.94	0.98	0.94	0.97	0.99	0.95	0.98	0.97	0.88		0.91	0.99	1.00	0.95	0.97	0.98	0.96	1.00	0.97	0.96
0.96	0.94	0.94	0.95	0.99	0.97	0.95	0.96	0.90	0.99		0.90	0.93	0.90	0.89	0.89	0.89	0.88	0.97	0.91	0.93
0.96	0.91	0.98	0.96	0.97	0.98	0.97	0.96	0.95	0.98		0.97	0.96	0.94	0.94	0.95	0.93	0.97	1.00	0.95	0.85
0.96	1.00	0.98	0.97	0.90	1.00	0.98	0.96	0.94	0.96		0.89	0.95	0.90	0.97	0.88	0.92	0.96	0.93	0.97	0.98
0.99	0.98	0.97	0.92	0.96	0.95	0.91	0.93	0.94	0.95		0.89	0.96	0.98	0.93	0.92	0.96	0.91	1.00	0.93	0.97
0.99	0.99	0.98	0.87	0.94	0.96	0.91	1.00	0.92	0.91		0.89	0.96	0.96	0.93	0.99	0.90	0.98	0.89	0.89	0.98
0.98	0.96	0.98	0.97	0.97	0.97	0.96	0.89	1.00	0.92		0.88	1.00	0.85	0.91	0.89	0.97	0.95	0.98	0.94	0.98
1.00	0.98	0.97	0.96	1.00	0.99	0.97	0.95	0.91	0.99		0.96	1.00	0.99	0.93	0.90	0.97	0.94	0.99	0.88	0.94
c											d									
0.78	0.78	0.72	0.74	0.63	0.66	1.00	0.88	0.71	0.82		0.67	0.69	0.71	0.82	0.59	0.67	0.80	0.72	0.83	0.53
0.89	0.88	0.79	0.88	0.81	0.87	0.85	0.92	0.94	0.99		0.79	0.81	0.78	0.70	0.96	0.86	0.67	0.87	0.87	0.80
0.91	0.73	0.90	0.91	0.71	0.84	0.61	0.91	1.00	0.93		0.71	0.75	0.82	0.86	0.54	0.95	0.57	0.90	0.68	0.94
0.77	0.64	0.77	0.82	0.77	0.70	0.70	0.94	0.91	0.83		0.73	0.93	0.64	0.80	0.85	0.73	0.83	0.98	0.83	0.84
0.85	0.71	0.80	0.86	0.95	0.86	0.64	0.89	0.84	0.82		0.71	0.75	0.51	0.92	0.89	0.91	0.60	0.92	0.69	0.83
0.99	0.94	0.96	0.94	0.93	0.94	0.78	0.87	0.88	0.86		0.90	0.93	0.79	0.82	0.93	0.92	0.76	0.79	0.86	0.83
0.70	0.54	0.82	0.73	0.63	0.76	0.94	0.94	0.87	0.93		0.67	0.73	0.79	0.69	0.80	0.73	0.87	0.94	0.74	0.91
0.87	0.88	0.78	0.93	0.93	0.81	0.72	0.92	0.87	0.87		0.87	1.00	0.82	0.93	0.79	0.80	0.74	0.84	0.79	0.95
0.93	0.96	0.92	0.88	0.84	0.86	0.81	0.91	0.96	0.91		0.86	0.96	0.75	0.76	0.89	0.86	0.67	0.82	0.88	0.80
0.68	0.77	0.76	0.83	0.83	0.94	0.84	0.88	0.90	0.92		0.85	0.81	0.73	0.80	0.93	1.00	0.76	0.86	0.76	1.00
e											f									
0.81	0.69	0.81	0.78	0.88	0.69	0.64	0.93	0.85	0.77		1.00	0.62	0.73	0.72	0.69	0.67	0.98	0.72	0.93	0.60
0.88	0.86	0.97	0.80	0.87	0.88	0.69	0.89	0.81	0.84		0.72	1.00	0.80	0.79	1.00	0.82	0.94	0.91	0.87	0.86
0.86	0.90	0.95	0.95	0.87	0.85	0.79	1.00	0.89	0.97		0.87	0.94	0.95	0.96	0.47	0.96	0.69	0.81	0.81	0.75
0.68	0.74	0.67	0.66	0.85	0.84	0.91	0.93	0.76	0.81		0.78	0.63	0.69	0.94	0.90	0.71	0.87	0.92	0.80	0.68
0.90	0.60	0.85	0.81	0.92	0.92	0.60	0.92	0.83	0.96		0.76	0.78	0.57	0.85	1.00	0.80	0.67	0.86	0.73	0.91
0.82	0.89	0.91	0.84	0.88	0.96	0.77	0.90	0.89	0.93		0.74	0.84	0.91	0.82	0.88	0.95	0.84	0.86	0.96	0.89
0.77	0.80	0.83	0.82	0.66	0.67	0.85	0.89	0.85	0.98		0.45	0.91	0.87	0.78	0.59	0.76	0.90	0.89	0.78	0.86
0.86	0.84	0.88	0.83	0.81	0.92	0.64	0.92	0.79	0.96		0.85	0.82	0.68	0.84	0.87	0.76	0.65	0.96	0.77	0.85
0.99	0.86	1.00	0.90	0.85	1.00	0.73	0.81	0.96	0.96		0.88	1.00	0.74	0.88	0.87	0.89	0.75	0.84	0.79	0.80
0.74	0.82	0.82	0.84	0.86	0.93	0.86	0.89	0.83	0.91		0.71	0.87	0.82	0.83	0.82	0.88	0.88	0.82	0.82	0.89

Fig. 3. Set of DoH matrices obtained every 15 days after the Round-Robin tests carried out on the aluminum structure, from (a) initial state to (f) final state.

There is a second approach to the health state of the structure when the average of the coefficients of the DoH matrix is calculated. Because of the progressive and sudden damage applied to the structures, the average decreases with time, no matter the type of tests (figure 4). Note that temperature affects the measurements taken in the tests.

Not only the average but also some other statistics will be analyzed as truncated mean, harmonic mean, median, standard deviation, etc.

5. Conclusions

The proof of concept for impact and flaw detection has been introduced. The methodology to perform guided-wave ultrasound tests has been detailed. The tests have been carried out on aluminum, CFRP, and a real-world leading edge. Round Robin and beamforming techniques have been applied to the tests. The effects of sudden and progressive damages on the health and integrity of the structures were analyzed.

Three approaches to analyze the data from the acquired signals have been introduced: calculation of DoH matrix, calculation of the average of DoH matrix, and comparison of acquired signals. The results show that the monitoring system SHMUS not only detects impacts and flaws satisfactorily but also measures the damage as a decrease of the health of the structure under test.

During the two months of tests, we performed more than 800 tests, which led to the acquisition of more than 100,000 signals. Nowadays, we are processing all these data.

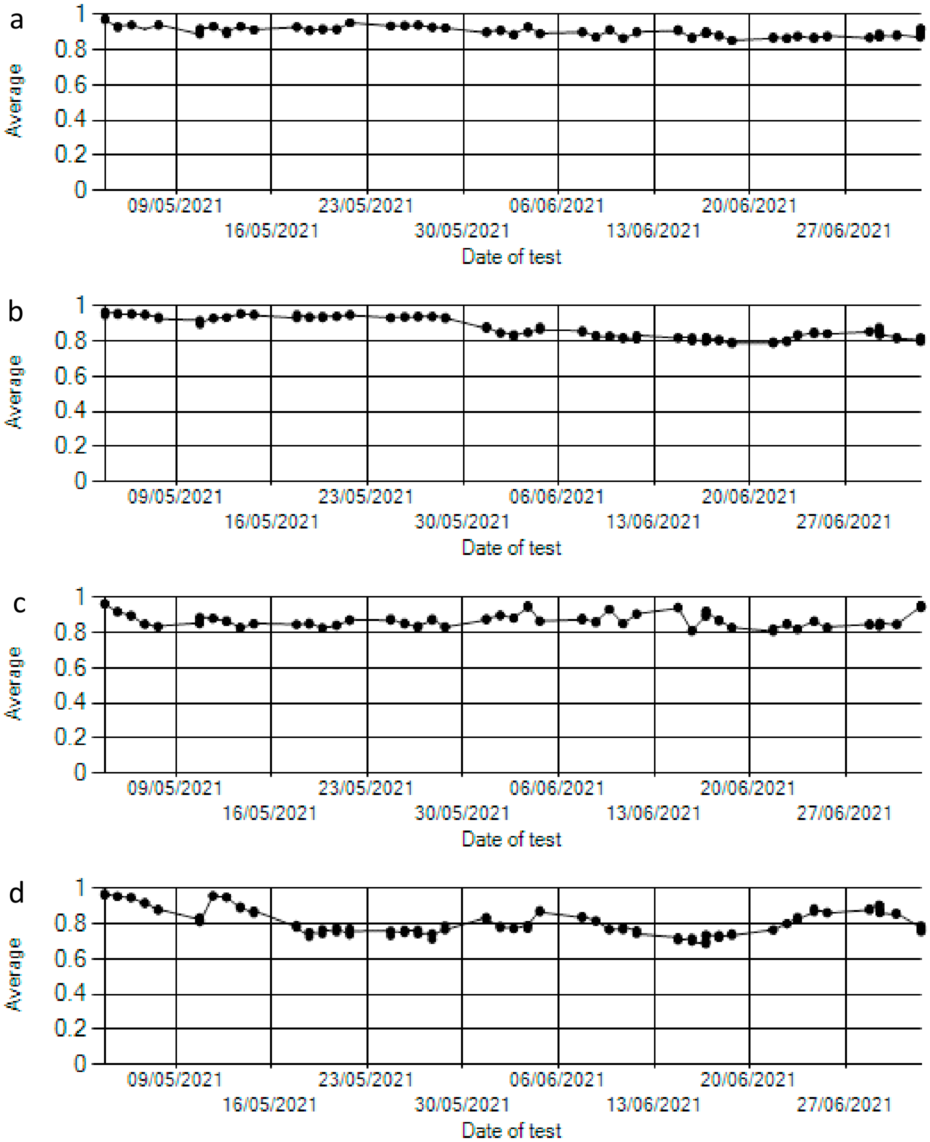

Fig. 4. Average of the DOH matrix: a) Beamforming in aluminum, b) Round-Robin in aluminum, c) Beamforming in CFRP, d) Round-Robin in CFRP.

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