Damage detection in composite structures using autonomous wireless systems: simulation & validation

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Abstract. In the European FP6 project ADVICE, units that harvest energy from structural vibrations have been developed. These autonomous units are capable of wireless communication and are used as actuators of guided ultrasonic waves used to identify changes in structural behaviour. The growing use of composite structures in aeronautics brings new challenges to be able to predict and detect damage that may occur in these new materials. Part of the ADVICE project focused on studying the possibilities of damage detection in structures using Lamb waves. In order to do this, finite element simulations were performed and were compared with experimental data. This paper presents the finite element simulations performed to predict the behaviour of a structural health monitoring system. Using the technique and algorithms developed to quantify the amount of damage, we compare the numerical results to those that were obtained experimentally on a small representative composite structure. This allows evaluating how it is possible to design a monitoring system for composite structures and what needs to be addressed in the future.

1. Introduction

Maintenance and safety are two key aspects of aeronautical structures as these often play an important role in the overall operational costs of aircrafts. Structural health monitoring is a field of research attracting much attention, given the potential impact it may have on the strategies and philosophies behind maintenance repair and overhaul operations. Structures undergoing continuous monitoring to detect changes in their behaviour and possible damage are seen as a promising solution in the move towards new maintenance philosophies and technologies. Recently, different solutions have been developed for real time damage detection in composite structures. Some of the most developed techniques are based on fibre Bragg gratings [1], acoustic emission [2] or can be based on impedance measurements [3]. In this paper the damage detection technique is based on Lamb waves, which is an active technique that allows monitoring areas of several square meters in thin structures.

1.1. Outline of the ADVICE project

The ADVICE project is a three year project that started in 2006 and gathers ten different industrials, research centres and academic partners. It is a multidisciplinary research project that aimed at the development of state of the art technologies for structural health monitoring and vibration damping in aeronautical structures, bringing together different research activities.

The partners involved in the project are:

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1.2. Project objectives

The objective of ADVICE was to design, model, develop and validate a smart wireless network of self-powered devices used for simultaneous damping of structural vibrations and detection of damage in airplane and helicopter structures. These devices were named VDCus (Vibration and Damage Control units). Emphasis was put on the wireless and autonomous aspects to limit cabling proliferation. To do this, the system harvests vibration energy from adjacent zones of the structure and use radio waves for data transmission [4].

We can identify three categories in the scientific objectives of the project:

- Development of a Vibration and Damage Control unit: including the development and optimization of non-linear processing techniques (synchronized switch) for harvesting and damping, constrained layer damping techniques, power management and Lamb wave transducer designs.
- Development of a smart network based on low power RF transmission modules for VDCu identification and communication, setup in a network with routers and gateways with AODV (On Demand Distance Vector Routing) algorithms, looking to minimize energy consumption.
- Damage identification and damping performance using novelty detection and pattern recognition algorithms for the determination of the damage signature / index, including the development of a user friendly interface for data analysis with dedicated hardware.

These different categories and in particular the last one rely on numerical predictions. We focus in this paper on simulations and experimental validation of detection of damage in the composite plate and prediction of the expected damage signature and mechanical response in terms of vibrations for the safe and damaged part.

1.3. System development

The VDCus that were implemented in the frame of the project were used to prove the feasibility of objectives pursued by the ADVICE consortium. They still require optimization and becoming more robust, but allow for a first evaluation of the energy balance on a representative composite structure. Below on the left is an illustration of the VDCu electronics assembled on a 4x4cm PCB board and on the right is the stiffened composite panel placed on a shaker that was used to characterize the system.
Piezoelectric patches, glued on the structure for vibration harvesting are visible on this image. Electronics are placed above the piezoelectric patches and connected before being eventually encapsulated.

![Figure 2. VDCu Electronics and piezoelectric patches installed on the structure](image)

While in flight, the strain created by structural vibration in the piezoelectric elements is converted into a direct current that is stored in a capacitor. This allows the VDCu to operate during flight and for a short while after all vibrations have stopped. To operate correctly, the VDCu needs to harvest roughly 0.2mW (depending on the communication cycle) with a Lamb wave sent every 10 seconds. Tests done on a shaker with different vibration spectra representative of aircraft structures showed that this is usually possible. The sensor on the other hand requires much more energy as RF needs to be constantly activated (RF communication is established with VDCu before any Lamb wave is transmitted) and the microcontroller has to handle more data. During the testing phase, sensors were thus externally powered.

Damage in the structure is evaluated using guided ultrasonic waves (also known as Lamb waves), that are generated by the VDCus, while end-nodes act as sensors which then compare the signal with a reference that is stored in the memory. Each signal is then sent to a central station that uses the signals from individual VDCus to evaluate the structural health of the zones undergoing monitoring. A neural network was used in the frame of the project to evaluate the probability of damage in the structure. The overall damage in a zone is evaluated by the neural network with a “Maintenance action” – a number between 0 and 1. If the maintenance action is above 0.7, the damage is considered confirmed. Under this value, the change in the structural response is lower than the threshold that was set.

2. Damage detection using Lamb waves

2.1. Lamb wave physics

Lamb waves are guided waves propagating in plate-like structures. The mathematical formulation of these two-dimensional modes with respect to the boundary conditions of a propagation medium limited in one direction (towards the plate thickness), was originally proposed by Lord Horace Lamb [5].

Two modes called fundamental modes are of particular importance in structural health monitoring since they do not have cut-off frequencies and they generally carry most of the acoustic energy. In health monitoring applications, Lamb waves are of particular interest because the fundamental modes travel through the whole thickness of a panel and also because their propagation is affected by local changes in the structure. Any discontinuity can create reflections of the wave, dissipate energy or convert the nature of propagating modes. In comparison with most of bulk waves-based techniques
Lamb waves have the advantage of propagating over quite long distances without appreciable attenuation.

Finally, the multimodal nature of the method makes it possible to exploit the specific sensitivity of each Lamb mode to different kinds of defects. It is thus conceivable to use this multimodal approach for the discrimination of the defects.

2.2. Lamb wave structure evaluation

Lamb waves were successfully used for the long-range non-destructive evaluation of pipes [6] or for corrosion-induced damage detection [7]. They were also largely used for the characterization of bonds [8], welds and joints. The high sensitivity of pulse-echo signals to the presence of cracks in aluminium plates is demonstrated with piezoelectric transducers [9].

In composite materials, Lamb waves are used to detect various defects such as delamination, porosity, ply gap, presence of foreign material and changes in fibre volume fraction of carbon/epoxy laminates [10]. Lamb waves were also compared to the normal incidence pulse-echo approach for the detection of near-surface delaminations [11]. Damage detection in various composite structures such as laminates, sandwich beams, pipes, and stiffened plates is allowed by Lamb-wave scans using piezoelectric actuators [12].

Numerous fundamental contributions intend to give a better understanding of the physics of the interaction between Lamb waves and localized defects using numerical tools such as the Local Interaction Simulation Approach (LISA [13],[14]). Others use the Finite Element Method (FEM) or the Spectral Element Method.

3. Lamb wave simulations

The simulation of Lamb wave propagation in structures was done using the finite element method. A complete 3D model is used in order to be able to take different effects into account such as delamination, stress distribution through the thickness due to fasteners and various damage configurations.

3.1. Workflow

The piezoelectric elements creating a stress wave through electric actuation are fully modelled in the simulations using linear piezoelectric equations and an implicit time integration scheme to derive the stress and displacement at the interface with the structure. The propagation of the ultrasonic wave is calculated using explicit time integration in order to speed-up and efficiently parallelizes the simulation.

![Figure 3. Workflow of the finite element simulations for wave propagation](image)

The diagram in Figure 3 illustrates the flow of information between three different models handling respectively the actuation, propagation and sensing of the ultrasonic wave. Important advantages of this technique are that:
Different levels of coupling between the piezoelectric material and the structure can be used.
An electric signal is used as input and obtained as output making it easier to compare simulations to experimental results.
Wall time on simulations can be drastically reduced compared to an all-implicit approach.

3.2. Composite panel
The composite panel used in the project is a 500x500mm carbon fibre reinforced polymer panel with an omega stiffener in one direction. RTM-6 resin and G0926 fibres are used to form a 1.85mm thick panel with 4.44mm increased thickness on the edges. The RTM process was used for manufacturing in order to have good repeatability of results and low porosity in the panels.

Ten different panels were used in order to reproduce results in a reference configuration and study different damage configurations. The stiffener was bonded to the composite panel and several holes were drilled on two sides. Dimensional inspections were then performed on each of the panels as well as modal identification.

The simulations were performed on a first order hexahedral mesh of the structure with 24 elements in the thickness and mesh size down to 1 mm. A size of 1.75mm was evaluated as sufficient in order to obtain converged results with the wave frequencies and material properties taken into consideration in the project [15]. The piezoelectric elements were modelled using second order elements with two elements in the thickness.

The damage types that were considered included delaminations, through holes and blind holes. The two later types of damage may seem less realistic, but allow a better control on the damage extent to be able to model it correctly in numerical simulations. Delaminations did not lead to exploitable results as the results with the Teflon strip inserted did not correlate to simulations, as it seemed that the Teflon did not affect the wave propagation sufficiently. Correlation between the model and the experimental results with through holes and blind holes are thus the only ones considered.

3.3. Results
Validation of the wave propagation simulations has already previously been done using results from literature on a long aluminium beam and a composite square panel [16], [17]. The structure studied here includes new geometric features including variable thickness, a bonded omega stiffener and fasteners on two edges of the panel.

Tests were performed in order to find an adequate actuation signal for the wave and the most appropriate location and size taking into account the manufacturing and other technical constraints. The figure below shows the stress distribution in two different plies of the panel at a given time step. The orthotropic properties of the panel are clearly visible as the stress distribution of the wave through the thickness of the composite panel follows the orientation of the fibres (0/90° or -45/45°).
Figure 6. Stress distribution in a 0°/90° (left) and -45°/45° (right) ply at 0.3 milliseconds.

Figure 7 shows the signal sent by the actuator. Figure 8 gives the voltage for the two transducers placed on the structure in an undamaged configuration and one in a damaged configuration (10mm diameter hole). Results from simulations showed that the peak signal amplitude arriving at the sensors on the opposite side of the panel will be two orders of magnitude lower than the amplitude of the signal sent by the actuator. Also, the stiffener will create a large amount of reflections that make it hard to interpret the signal visually after a short duration of time. Damage cannot be perceived in a similar way as when the structure is a simple 1-D beam.

![Input voltage generated by the VDCu electronics and emitted by the piezoelectric transducer](image)

**Figure 7.** Input voltage generated by the VDCu electronics and emitted by the piezoelectric transducer

The calculation of the damage index is done using the Fourier transform of the time signal. In order to maximize the probability of detecting the damage, a time and frequency window is applied to the signal based on the panel dimensions, material properties and frequency of the Lamb wave. In this case, the time window is limited to 0 to 0.005 seconds and the frequency window is limited from 2.5 to 10 kHz as the central frequency of the Lamb wave was 7.5 kHz as shown in Figure 9. The damage indexes for different damaged configurations are shown in Table 1 of the following section.

Although the difference in signals may seem quite small, the Fourier transform allows to focus only on the coefficients that are affected by damage which allows to derive a damage index that clearly identifies a change in structural response. Others have also used the 2-D Fourier or time-frequency analysis to identify structural changes with Lamb waves [18].
Figure 8. Electric signal (V) at the sensor emitted by the first VDCu (left) where the wave travels through the unstiffened area of the panel and by the second VDCu (right) where the wave has to cross the stiffener.

Figure 9. Fast Fourier transform of the signal used to calculate a damage index comparing amplitudes in a restricted frequency window.

4. Validation of damage detection

The experimental results in ADVICE were obtained once all the electronics were completed and could be used in order to create the actuation and sensing device. The signals were collected through the central station but also directly from the sensors by placing an additional output towards a standard digital signal processor with a higher resolution and sampling rate. The testing campaign included tests on the different panels at six damage intensity levels, testing the panel at different temperature levels as well as spraying one side of the panel with water.

The signals from simulations and measurements are compared in Figure 10. There is a good correlation between results for the first millisecond of the wave propagation, but differences appear after this due to the reflection of the wave on the multiple boundaries of the panel. The dissipation of the wave energy is difficult taken into account in the simulations as no experimental results on damping coefficient were made. The difference observed between the simulations and measurements increases over the duration of the signal.
Figure 10: Comparison between the simulations and experimental results for Lamb wave propagation over 2 milliseconds: time signal (left), fast Fourier transform (right)

Table 1 gives the values that were calculated to compare different signals using the fast Fourier transform. The indication that is used is called the Damage Index [19] and is defined as such:

\[ DI = \frac{|FFT_{ref} - FFT_{dam}|}{|FFT_{ref}|} \]  \hspace{1cm} (1)

| Panel \hspace{1cm} Damage \hspace{1cm} | Simulation Damage Indices \hspace{1cm} | Experimental Damage Indices \hspace{1cm} |
|----------------------------------------|---------------------------------|---------------------------------|
|                                       | VDCu1 \hspace{1cm} VDCu2        | VDCu1 \hspace{1cm} VDCu2       |
| Panel - 1 \hspace{1cm} None           | 0.000 \hspace{1cm} 0.000        | 0.035 \hspace{1cm} 0.14        |
| Through hole 8mm                      | 0.07 \hspace{1cm} 0.13          | 0.08 \hspace{1cm} 0.22         |
| Through hole 13mm                     | 0.11 \hspace{1cm} 0.19          | 0.12 \hspace{1cm} 0.24         |
| Panel – 6 \hspace{1cm} None          | 0.00 \hspace{1cm} 0.00          | 0.04 \hspace{1cm} 0.08         |
| Through hole 8mm                      | 0.07 \hspace{1cm} 0.13          | 0.095 \hspace{1cm} 0.15        |
| Through hole 13mm                     | 0.11 \hspace{1cm} 0.19          | 0.105 \hspace{1cm} 0.18        |

These results show first of all the important variability of measurements on the panels, especially with the signal coming from the second VDCu on panel 1 due to a low signal to noise ratio. Averaging several measurements before calculating the damage index may improve this. Also, results showed that two panels can give different values due to the varying boundary conditions (at the bolts) or slight differences in dimensions. Otherwise, the values found through simulations are similar to the ones found during the measurements and we can conclude that the effect of a simple damage on the frequency content of the wave can be correctly simulated in stiffened composite structure.

4.1. Training with the neural network

Signals are not only processed on an individual basis. The damage indices described above should be centralized and used together to evaluate the possible damage in a structure. A neural network processes the data that arrives at the central station in order to determine if the panel has sustained a critical amount of damage. This solution was chosen in order to have a generic way of processing data that could be used with other geometries or materials.

In order to obtain a functional neural network, training must be done with data that has initially been obtained. Generally, the training will lead to better results if we have a larger amount of training patterns with a maximum number of realistic scenarios. The architecture of the neural network is of prime importance too in order to be able to fit correctly the response function of the system. In our case, a simple two layer feed-forward network is used since the panel and damaged configurations are
quite simple. An auto-adaptive network may be more adequate to adapt to different structures and sensor networks, but this was out of the scope of this research.

The training patterns considered are shown in Table 2 and with them are shown the number of correct/failed diagnostics. A true positive/negative corresponds respectively to a case where the neural network correctly evaluated that there was/wasn’t significant damage while in false positive/negative, the neural network did not evaluate correctly the integrity of the structure. Signals from two different damage types, with six different damage sizes and four different locations were used making a total of 217 pairs of signals. A threshold was arbitrarily set for the damage size that has to be detected. The two highest damage sizes (10 to 20mm diameter) are considered critical, while the smaller damages (<10mm) do not have to set off a warning. Several interesting conclusions can be made already from these first results:

- Using only healthy data for training does not allow detecting the occurrence of damage. In order to cope with this, a confidence level was introduced, which indicates if the data that is fed in the neural network is similar or not to that which was used for training. To set the parameter calculating the confidence, at least one signal from a damaged configuration must nevertheless be available.
- The evolution of the damage size could be predicted by the neural network, but the accuracy depended on the similitude of the damage type and location compared to the ones used for the training of the neural network.
- Changing the environmental parameters (temperature, humidity) also affects the signals and should be taken into account. Tests made at different temperatures lead to very different signals that the neural network can process, but using the temperature as an input for the neural network should be used to detect damage regardless of the ambient temperature.
- Finally, the data and training from one panel can be used for another similar panel. Although the neural network threshold between a damaged and undamaged panel will be less precise, over ¾ of the cases are correctly identified. Having a network capable of continuously improving and updating its parameters based on collected and validated data will give better results as data is analyzed.

### Table 2: Neural network validation results based on different training patterns

| Training         | Validation | True Negative | True Positive | False Positive | False Negative |
|------------------|------------|---------------|---------------|----------------|----------------|
| All data         | All data   | 1.0           | 0.9           | 0.0            | 0.1            |
| 50% of data      | All data   | 0.92          | 1.0           | 0.08           | 0.0            |
| 25% of data      | All data   | 0.99          | 0.95          | 0.01           | 0.05           |
| Only panel 6     | All data   | 0.81          | 0.77          | 0.19           | 0.23           |
| All healthy      | All data   | 1.0           | 0.0           | 0.0            | 1.0            |

5. Conclusions and recommendations

In this article, we showed how finite element modelling can be used to predict the propagation of Lamb waves study damage detection in composite structures. Although the finite element model results do not show a perfect match with experimental results due to the high sensitivity of boundary and environmental conditions on Lamb waves, they do however predict quite accurately the effect of the holes drilled in the structure on the Lamb wave signature. The finite element method could be used to develop algorithms for damage detection and test possible damage configurations. The experimental and simulation results show that signal processing is required in complex heterogeneous structures in order to highlight the effect of a given damage. The Fourier transformation and damage index calculation used here are quite simple but already effective. Different tools have already been tested with Lamb wave signals and it would be interesting to integrate them in the current developments.
Numerical simulations can be of interest to include different damage cases in a training based method. There is interesting research to be conducted here as well as development of faster and more effective methods to predict the effect of damage on wave propagation in complex composite structures. Further development should consider a wider range of parameters that can influence the signal and sensors to try to achieve sufficient robustness in order to apply such tools in real applications on aircraft structures.

These results coupled with the other developments in the ADVICE project for low powered electronics show interesting possibilities that could be developed and exploited in order to achieve an autonomous wireless network used for structure monitoring. The project showed that such a system was feasible in a vibrating aircraft environment, but further work should be made to have a reliable and durable system.

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