Damage Identification using Guided Waves on a Composite Skin-Stiffener Structure

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Abstract
The potential of using guided waves for damage detection in composite materials has been proven by many researches in the past few years and in particular by the cases studies of the European project SARISTU. In that project integration methods for the piezoelectric wafer active sensors (PWAS), algorithms and a graphical user interface were developed, to allow for an easy to access analysis of the measured data. Despite the proven potential, there is still a large number of questions to be answered before the guided wave based damage identification can be extended from detection to a fully automated, robust and reliable damage identification. This requires a further understanding of the behaviour of guided waves travelling through a multi-layered composite material. To this end, a 16 layer carbon fibre reinforced PEKK thermoplastic, with cobonded T-shaped stiffeners, panel is instrumented with 16 PWAS. An impact is applied to the structure, after measurements of the pristine structure, to inflict a delamination damage underneath one of the stiffeners. Previous research has revealed impact causes first ply failure and skin-stiffener debonding.

Keywords: guided waves, waveform, damage identification, composite structures

1. INTRODUCTION
The potential of using guided waves for damage detection in composite materials has been proven by many researches in the past few years [1, 2] and in particular by the cases studies of the European project SARISTU. Important steps were made in that project on the one hand by developing integration methods for the piezoelectric wafer active sensors (PWAS) [3] and on the other hand by the development of algorithms [4, 5] and a graphical user interface [6, 7] to allow for the analysis of the measured data without the need for detailed knowledge on guided wave based damage identification. The software, capable of dealing with experimental and numerical data, offers on the one hand the possibility to control a series of settings to investigate specific features of the damage identification process and find the optimum settings. On the other hand, the software can be used with a limited level of knowledge on wave propagation theory, relying on the standard settings that already provide satisfactory damage identification capabilities [4, 6]. Despite the proven potential, there is still a large number of questions to be answered before the guided wave based damage identification can be extended from detection to a fully automated, robust and reliable damage identification, including the nature and extent of the damage. The layered, anisotropic structure of fibre reinforced plastic complicates the analysis and interpretation of the wave signals, as pointed out by Su et al. [1], making it difficult to simulate numerically how the waves propagated. An extensive overview of the methods applied for the simulation of propagating waves is provided by Wilberg et al. [8]. The general trend is that numerical solutions for complex structures are still (too) computationally expensive.

Without discarding the contribution of numerical models to understand the wave propagation in composite materials, experimental investigations are a highly suitable method to reveal the critical parameters in a lamb wave propagation based damage identification methods. This is for example shown by the efforts
of the EU FP7 project SARISTU to apply the methods on a real, full scale structure [3]. The experimental work discussed here aims to support the development of the analysis techniques in the damage identification software, making them more robust and reliable as well as expanding their applicability.

2. GUIDE WAVES & DAMAGE IDENTIFICATION

The piezo-electric transducers send different types of propagating wave into the structure. The objective is to generate first antisymmetric and symmetric (A0 and S0) guided waves in the structure. The S0 waves travel faster – and further – and have a lower attenuation and lower dispersion than A0 waves [1, 2]. The S0 waves have proven to be suitable for the detection of damage anywhere in the structure, whereas A0 waves tend to be good at the identification of delaminations and transverse crack. Other advantages of the A0 waves is their higher amplitude, shorter wavelength (hence, higher resolution) and easier of actuation [9].

The identification of damage based on guided waves relies on the comparison of the signals travelling from one transducer to another before and after the damage and – on top of that – a probability based reconstruction of the damage location by combining the information of all actuator-sensor paths [4, 5, 10]. The damage intensity probability \( I \) at an arbitrary position \((x,y)\) is given by:

\[
I(x,y) = \sum_{k=1}^{N_p} \left[ 1 - \rho_k \left( \frac{\beta - R(x,y)}{\beta - 1} \right) \right]
\]

with \( \rho_k \) being the damage indicator of the \(k\)th actuator-sensor path, \(N_p\) the number of paths and \(\beta\) a scaling factor determining the area of influence. \(R(x,y)\) is modified by Moix-Bonet et al. [5] by introducing the scaling factor \(\alpha\) to modify the shape of the probability distribution function and reads:

\[
R(x,y) = \begin{cases} 
\frac{\sum_{k=i,j} \sqrt{(\Delta x_k + q \alpha \Delta x_{nm})^2 + (\Delta y_k + q \alpha \Delta y_{nm})^2}}{(1 - 2 \alpha) \sqrt{\Delta x_{nm}^2 + \Delta y_{nm}^2}} & \text{for } R(x,y) < \beta, q = \begin{cases} 1 & \text{for } k = i \\ -1 & \text{for } k = j \end{cases} \\
\beta & \text{for } R(x,y) \geq \beta 
\end{cases}
\]

where \((x_k, y_k)\) and \((x_{nm}, y_{nm})\) indicate the locations of transducer \(n\) and \(m\) respectively. Typically, \(\beta\) is equal to 1.05, but here, \(\alpha\) and \(\beta\) is optimised based on minimisation of blind zones, deviation in probability distribution values and the kurtosis [5].

The damage indicator \(\rho\) is essentially a condensation of the difference(s) between the reference signal and the current signal to a single number. Typically, the correlation coefficient between the two signals is used [1, 2], but there is a range of methods that can be used to calculate this index [6, 10]. The results acquired in the SARISTU project revealed four damage identification algorithms as suitable candidates for the structure and type of damage at hand [4]. Here, only the correlation coefficient will be used, defined by:

\[
\rho = \frac{\sum_{i=1}^{N} \left( S_{H,i} S_{D,i} \right) - \frac{N}{\sum_{i=1}^{N} \left( S_{H,i} \right)} \frac{N}{\sum_{i=1}^{N} \left( S_{D,i} \right)}}{\sqrt{\sum_{i=1}^{N} \left( S_{H,i}^2 \right) - \left( \frac{N}{\sum_{i=1}^{N} \left( S_{H,i} \right)} \right)^2} \sqrt{\sum_{i=1}^{N} \left( S_{D,i}^2 \right) - \left( \frac{N}{\sum_{i=1}^{N} \left( S_{D,i} \right)} \right)^2}}
\]

3. EXPERIMENTAL WORK

A composite panel with three T-shaped stiffeners is instrumented with 16 PWAS. The panel, a carbon fibre reinforced PEKK thermoplastic, with co-bonded T-shaped stiffeners has a 16 layer midsection (2.1mm thickness, quasi-isotropic layup), while the end sections are thickened (30 and 44 layers).
PWAS transducers are circular PI DuraAct (PIC255) transducers with a diameter of 10mm and a thickness of 0.2mm, bonded with an epoxy adhesive to the structure.

![Figure 1: Schematic of the experimental set-up, using the center eight transducers for the acquisition, while other combinations are also possible. The actuation signal is sent by the HandyScope HS3, connected to one of the transducers. The HandyScope HS4’s are collecting the signals from the transducers.](image)

A schematic of the experimental set-up is given in fig. 1. The HandyScope systems HS3 and two HS4 are used for the interrogation of the structure. Different combinations of 8 transducers can be used, listed in table 1. All transducers in each configuration are sequentially assigned as the actuator, while the others are sensing the signal.

<table>
<thead>
<tr>
<th>Set</th>
<th>PWAS sensors</th>
</tr>
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<tbody>
<tr>
<td>1.</td>
<td>1 2 3 4 5 6 7 8</td>
</tr>
<tr>
<td>2.</td>
<td>1 2 3 4 9 10 11 12</td>
</tr>
<tr>
<td>3.</td>
<td>5 6 7 8 13 14 15 16</td>
</tr>
<tr>
<td>4.</td>
<td>10 2 6 14 9 1 5 13</td>
</tr>
<tr>
<td>5.</td>
<td>11 3 7 15 10 2 6 14</td>
</tr>
<tr>
<td>6.</td>
<td>12 4 8 16 11 3 7 15</td>
</tr>
</tbody>
</table>

The actuation signal is a sine burst of 5 periods, multiplied by a Hanning window and with an amplitude of 12 Volts, which is the maximum output voltage the HS3 arbitrary waveform generator can supply. The signal received by the sensors is in the order of tenths of millivolts. To improve the signal to noise ratio, each measurement is repeated 50 times. The signal used for further processing is the acquired by cleaning and averaging the response from the 50 measurements. The actuation frequency has been varied from 25 to 100 kHz. Results from the SARISTU project revealed that the best results were obtained for actuation frequencies in the range of 50-60 kHz [4].
The cleaning of the data started with down sampling the 128000 points of each measurement (the maximum record length of the HandyScope systems) to 25 points and fitting a cubic spline function through these points. The fitted function is considered to be the instantaneous offset of the signal and subtracted from the raw signal. Subsequently, the mean of the 50 measurements is taken to reduce the noise in the signal.

4. IMPACT DAMAGE

Impacts were applied to the structure, after measurements of the pristine structure, to inflict a representative delamination damage underneath the stiffeners. Previous research has revealed impact causes first ply failure and skin-stiffener debonding [11, 12]. The impact damage was applied to the structure by a sequence of impacts. The reason to opt for a sequence rather than a single impact was that the impact strength of the panel was unknown. Initially, a 10 mm diameter tub was used, which resulted in a clearly visible impact on the structure. A second impact damage was created, again with a sequence of impacts, with a 25.4 mm diameter tub. This resulted in a barely visible dent, equal in depth to other regions with surface unevenness resulting from manufacturing but with a suspected internal delamination damage. The method of impacting gave distinct impacts, which is useful, although it is recommended to use the energy levels obtained from these tests to apply a single impact for subsequent impacts. Visually, the two damages are clearly different. At this moment in time, the panel has not yet been subjected to a thorough non-destructive evaluation, using ultrasound, to assess the differences in the non-visible, internal damage. However, it is expected that the waves passing or crossing the damage will be affected differently.

5. RESULTS & DISCUSSION

With the objective being to gain more insight in the effect of both a stiffener and a damage on the acousto-ultrasonic waveform, three different aspects are investigated firstly:

1. The effect of the stiffener on the waveform
2. The path reciprocity with and without damage
3. The effect of damage on the waveform

Finally, damage probability plots, using (1), (2) and (3), are made with the software developed in the EU project SARISTU [7].

5.1 Effect stiffener on waveform

The PWAS transducers are placed on an equidistant grid. Hence, paths are available with equal path length, but with either no stiffener or one up to three stiffeners on the path. It is expected that the attenuation of signal will be higher if the wave pack passes a stiffener, but generation of higher order waves is also possible; the frequency of actuation plays a key role. The waveforms of two actuation frequencies, 50 kHz and 90 kHz, are shown in fig. 2. Both waveforms in each graph are the result of the same actuation signal, but retrieved by a sensor located in parallel or perpendicular direction with respect to the stringer. The solid line corresponds with the waveform from the path without a stiffener, whereas the dashed line corresponds with that in the presence of one stiffener. The path length is 135 mm. The first part of the signal, around 1 millisecond, is caused by electro-magnetic interference. In case of the 50 kHz actuation, the amplitude of the response between 1.1 and 1.2 milliseconds is lowered due to the presence of the stiffener. This response is associated with the first, antisymmetric fundamental wave, given the relatively high amplitude and the relatively low actuation frequency. A delay of the maximum of the wave pack appears to be present as well, indicating a small amount of dispersion. The signals show a low correlation after 1.25 milliseconds, most likely caused by refractions and reflections.
The response in case of a 90 kHz actuation frequency does, on the contrary, not show a decrease of the amplitude, but a significant increase. This is likely to be attributed to additional wave generation. The wave length of the higher frequency is in the order of magnitude of the thickness of the foot of the stiffener. This may cause other wave forms to be generated, explaining the forward shift of the wave pack arrivals (just before 1.05 millisecond) and just after 1.1 millisecond).

The change of the response is representative for the signal on similar paths in the same and in other sets of transducers, although the increase in the amplitude is not always as large as in the case shown here.

Comparing the waveforms of paths that are similar in length, but cross two or three stiffeners bears the difficulty that different experiments must be compared: results from paths of the workspaces oriented parallel to the stringers and of those oriented perpendicular to the stringers must be compared. However, most of the results show a high degree of consistency. Those results that deviate appear to be affected by other external reasons. This is still subject of investigation.

The waveforms of two representative cases with an actuation frequency of 50 kHz and two of 90 kHz are shown in fig. 3.

In all cases a strong attenuation of the waves is found. The higher amplitudes in the response of the 90 kHz signal on a path with a single stiffener (fig. 2b) is consistently attenuated in the waveforms for paths with more than one stiffener; the remainders of this can be seen around 1.1 ms in fig. 3b.

5.2 Path reciprocity with and without damage

Generally, the path is only analysed once, assuming that the signal travelling from one transducer to the other is the same as when the signal would travel in the other direction. This assumption is valid from a theoretical perspective, assuming the inhomogeneities are negligible. It is, strictly taken also only valid
in the pristine case. This may not be a problem for the damage detection, but it is possible that valuable information for the damage identification is ignored.

The waveforms of the paths PWAS 2 to PWAS 7 (solid line) and vice versa (dashed line) are shown in fig. 4. The actuation frequency is $50\,\text{kHz}$, but the conclusions on the results shown are also valid for the other actuation frequencies. According to the expectations, the waveforms for the pristine case (fig. 4a) are identical apart from some very minor differences. More surprisingly, the waveforms are also identical in the damaged case (fig. 4b). The path selected crosses the damaged region. This seems to imply that the damage is midway of the path and (close to) symmetrical. The impact is applied very close to the stringer, as this will be the first location where the structure will fail, and in the middle of the plate, as a result of the limitations of the impact set-up. Hence, the impact location is nearly, but not exactly, midway of the path. A non-destructive evaluation of the internal damage has not yet been performed, but is likely to shed more light on this.

The only exceptions on these results concern the waveforms obtained with PWAS 1 as the actuator. This waveform deviates significantly from the other waveforms. This is caused by problems with the PWAS or its connecting wires. Impedance measurements are planned to check the quality of the PWAS.

### 5.3 Effect damage on waveform

The ultimate goal of this research is to develop a damage assessment tool. The better the effect of the damage on the waveform is understood, the more powerful the tool will be in identifying a damage. The prime objective is thus to investigate the way the different damages affect the waveform. Two different
impact damages are compared, resulting from the impacts, as discussed in section 4.

The waveforms of the signal from PWAS 2 to PWAS 7 of sensor set 1 (see table 1) and that from PWAS 7 to PWAS 14 of sensor set 5 are shown in fig. 5, for an actuation frequency of 50 kHz. Both paths have the same length ($\approx 190.9$ mm) and cross the damage location. The signals already differ for the pristine case. The explanation for these differences are to be found in sensor and material inhomogeneities. More importantly, the effect of the damage on the signal is different. For the first damage, the waveform shows an increase in amplitude around 1.13 ms, compared to the pristine case. This could be the result of a newly generated higher order wave. The second damage does not introduce an amplitude increase before, but shows an amplitude increase only after the part of the signal with the higher amplitude ($\approx 1.15$-1.22 ms in fig. 5a and $\approx 1.17$-1.24 ms in fig. 5b). The signal appears to be more dispersed as well in the latter case.

### 5.4 Damage Intensity Probability

The differences between the waveforms can disappear when calculating the damage indicator $\rho$, since the algorithms, such as the correlation coefficient, defined in (3), only provide a value representing the amount of difference. The way the signals differ is not reflected in this value. The damage intensity probability is plot (fig. 6 and fig. 7), using the software developed in the EU project SARISTU [7] for the two different impact damages and the two actuation frequencies analysed in this paper (50 and 90 kHz). The sensor sets 1, 3 and 5 were used, as listed in table 1.
1.05 1.1 1.15 1.2 1.25 1.3 1.35 1.4 1.45 1.5

a: Waveforms of the signal from PWAS 2 to PWAS 7 of workspace 1 for the pristine (solid line) and damaged (dashed line) case after the first impact.

-6 -0.02 0.02 6

Signal Amplitude [V]

1 1.05 1.1 1.15 1.2 1.25 1.3 1.35 1.4 1.45 1.5

time [ms]

b: Waveforms of the signal from PWAS 7 to PWAS 14 of workspace 5 for the pristine (solid line) and damaged (dashed line) case after the second impact.

Figure 5: Waveforms in pristine and damaged case after the two subsequent impacts. The actuation frequency was 50 kHz.

The fifth sensor set is used to plot the damage intensity probability for both impacts. The measurement after the first impact is therefore taken as the reference for damage intensity probability plot after the second impact – fig. 7(b) and (d).

The signal between PWAS 1 and PWAS 2 was found to be distorted, as mentioned earlier. This is reflected in the yellow colour between point 1 and 2 in fig. 6(a) and (c). This heavily influences the visibility of the real damage location in the center of the image. However, the shape of the coloured area in the center of the image does not appear to show significant differences with that of the third sensor set, shown in fig. 6(b) and (d). Likewise, the actuation frequency does not alter the results, although the waveforms showed significant differences.

More significant differences are observed in the results of sensor set 5. First of all, the first impact damage seems to have a weaker response, compared to that of the second impact, despite the fact the damage is more visible. However, the scaling of the plots is not equal, thus leading to the conclusion that the damage may cover a larger area, or at least influences the signals of more paths, compared to the second impact. Another difference is that the actuation frequency does influence the results.

Finally, it is noteworthy that the presence of the stringers was shown to affect the waveforms significantly, but this is not, or at least not directly, reflected in the damage intensity probability plot.

6. CONCLUSION & FUTURE PROSPECT

The investigation of the waveforms for different paths, with or without stringer, and different impact damages has revealed that the waveforms are consistently comparable over equal paths, but certainly
affected by the presence of a stiffener. The different damages were also affecting the waveforms in specific ways. At this moment it is not yet possible to link the type of damage to specific changes; for this step, a more detailed analysis of both the waveforms and the damage is needed. C-scans of the panel are scheduled to acquire the necessary data for the latter point, while the analysis of the waveforms will include various signal processing steps to improve the quality of the data (remove noise elements).
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