Damage Quantification in Aluminium-CFRP Composite Structures using Guided Wave Wavenumber Mapping

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Abstract
The use of composite materials is associated not only with the advantages of weight reduction and improved structural performance but also with the risk of barely visible impacts or manufacturing damages. One of the promising techniques for the detection and characterisation of such damages is based on ultrasonic guided wave propagation and analysis. However, the multimodal nature and dispersive behaviour of these waves make their analysis difficult. Various signal processing techniques have been proposed for easier interpretation of guided wave signals and extraction of the necessary information about the damage. One of them is the wavenumber mapping which consists of creating a cartography of the wavenumber of a propagating mode over an inspected area, using a dense wavefield acquisition measured for example with a scanning laser Doppler vibrometer. This technique allows both the quantification of the in-plane size and the depth of damage, for example, impact-induced delamination in composite laminates.

In this contribution, wavenumber mapping is applied to a delaminated aluminium-CFRP composite plate which corresponds to the structure of composite-overwrapped pressure vessels used for storing gases in aerospace and automotive industries. The analysis of experimental data obtained from the measurements of guided waves propagating in such composite plate with impact-induced damage is performed. The output of the imaging is a three-dimensional representation of the delamination induced by the impact. Good agreement between conventional ultrasonic testing and guided wave damage mapping can be found.

1. Introduction
The growing use of composite materials in aerospace and automotive applications is associated with weight reduction and improved structural performance. However, the risk of barely visible impacts or manufacturing damages exists which may be critical for the further safer use of the component. Therefore, there is a need in techniques that can detect and characterise damage. One of the promising techniques is based on ultrasonic guided wave propagation and analysis. Their multimodal nature and dispersive behaviour allow for the detection and characterisation of various damage types, however, making the analysis of guided wave signals difficult. For easier interpretation of the signals and extraction of the necessary information about the damage, advanced signal processing techniques have been proposed [1-7]. One of them is the wavenumber mapping which consists of creating a cartography of the wavenumber of a propagating mode over an inspected area. The mode is typically excited using a piezoceramic transducer and a wavefield is measured with a scanning laser Doppler vibrometer, since a dense acquisition is required for the successful analysis. This technique allows both the quantification of the in-plane size and the depth of damage, for example, impact-induced delamination in composite laminates [6, 7].

In this contribution, wavenumber mapping is applied to a delaminated aluminium-CFRP composite plate which corresponds to the structure of composite-overwrapped pressure vessels used for storing gases in aerospace and automotive industries. The analysis of experimental data obtained from the measurements of guided waves propagating in such composite plate with impact-induced damage is performed. Two cases are considered – for the measurements performed from the aluminium side and from the CFRP side of the composite plate. The output of the imaging is a three-dimensional representation of the delamination induced by the impact. The damage map obtained from the guided wave-based analysis is in a good agreement with the results from conventional ultrasonic testing.

2. Wavenumber mapping
2.1. Description of the techniques
There are two techniques which allow for the quantification of the local wavenumber, namely the Instantaneous Wavenumber (IW) and the Frequency Domain Instantaneous Wavenumber (FDIW) [6, 7]. For the sake of brevity, the mathematical operations are not presented here, and readers are referred to [8]. While the IW estimates the wavenumber from a measured wavefield at a time instant, the FDIW measures it from a single frequency wavefield. Thus, an IW map contains all the frequencies and corresponding wavenumbers of the excited modes. This complicates further analysis since the wavenumbers for each frequency contained in the wave packet have to be known. A FDIW map, in turn,
ideally delivers one wavenumber for each mode at the defined frequency.
To demonstrate both techniques the guided wave propagation was modelled in a 2 mm aluminium plate using the spectral element method of CIVA for efficient simulations of the guided wave propagation [9]. The plate was excited by a three-cycle burst at 150 kHz. At this frequency only S0 and A0 modes can propagate in the plate which are clearly visible in Fig. 1 (a). In this figure only the out-of-plane component is shown and the amplitude of the A0 mode is much larger than of the S0 mode. This time instance was chosen because the modes are spatially separated, thus the resulting IW map presented in Fig. 1 (b) directly estimates the wavenumbers of the modes. In this contribution, the Scaled Boundary Finite Element Method (SBFEM) is used to calculate all the dispersion curves [10]. The material properties shown in Table 1 were used to obtain the dispersion curves for the 2 mm aluminium plate. The resulting wavenumbers are 176 and 610 rad/m at 150 kHz for S0 and A0 modes, respectively. The estimated wavenumbers in Fig. 1 (b) are spread around these values, because the IW map contains all the frequencies excited. Since the wavenumber mapping does not preserve amplitude information, even very small amplitudes barely visible in Fig. 1 (a) deliver the wavenumber estimates. It is interesting to observe in Fig. 1 (b) that the front of the A0 wave front has a higher wavenumber value than the back, which is due to the dispersion (higher frequency with higher wavenumber being faster than lower frequencies).

Table 1: Material properties of aluminium, where \( E \) is Young’s modulus, \( \nu \) Poisson’s ratio and \( \rho \) density.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>( E )</td>
<td>70</td>
<td>GPa</td>
</tr>
<tr>
<td>( \nu )</td>
<td>0.33</td>
<td>-</td>
</tr>
<tr>
<td>( \rho )</td>
<td>2770</td>
<td>kg/m³</td>
</tr>
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Knowing the dispersion relation, the wavenumber can be directly related to the thickness for the defined frequency. Thus, to be able to quantify the depth of a damage, it is preferable to work with one mode at one frequency. For this, additional signal processing is necessary prior to the IW analysis. A three-dimensional Fourier transform is applied to the wavefield data, which allows to separate wavenumbers of propagating modes for each frequency by filtering in the wavenumber-frequency space [1]. Having this data, the frequency of interest can be selected for further analysis, for instance the excitation frequency of 150 kHz in this case. Then, only the mode which is the most sensitive to the thickness variation is left by filtering other modes in wavenumber domain. The resulting frequency slice is transformed using the inverse Fourier transform to retrieve a single frequency wavefield, which is shown in Fig. 2 (a). The wavefield covers the entire region as if the plate was excited continuously. The length of the time signal is chosen so that there are no reflections from the plate edges which would disturb the wavefield and subsequently the FDIW map. The IW algorithm is then applied to the wavefield and the resulting FDIW map is presented in Fig. 2 (b). The map shows almost uniform green colour which represents the wavenumber of A0 mode at the frequency of 150 kHz.

![Figure 1: (a) An exemplarily time frame of the guided wavefield in a 2 mm aluminium plate modelled using the spectral element method and (b) the corresponding IW map.](image)

2.2. Depth quantification
A damage such as a delamination, impact or corrosion damage leads to a change in the wavenumber of a mode due to an effective thickness change, where the effective thickness is defined as the depth of the pristine material below the scanned surface. Based on the dispersion relation this change can be used to calculate the effective thickness and by that to quantify the depth of the damage. To demonstrate this, a 20 x 20 mm² “delamination” at the depth of 1 mm was inserted into the aluminium plate and the simulation was performed using the spectral element method. This defect represents for example a lack of fusion in a stack of the aluminium plate, which could be observe in gluing operations or additive manufacturing. The resulting FDIW map clearly indicates the position and spatial extent of damage, see the orange square in Fig. 3 (a). What happens is that the A0 mode is propagating in the pristine region of the plate and when it encounters the delaminated region the mode splits into two independent modes, because the delaminated region is represented by two independent 1 mm plates. The A0 mode has the wavenumbers of 809 and 610 rad/m at the frequency
of 150 kHz for the 1- and 2-mm plates, respectively. Thus, in the delaminated region the wavenumber of 809 rad/m is expected, whereas the pristine region should have the wavenumber of 610 rad/m. These wavenumbers are clearly visible in Fig. 3 (a). Since the evaluation is performed at the plate’s surface, only the upper 1 mm plate is visible in the FDIW map. Using the dispersion relation of the A0 mode as a function of the Effective Thickness (ET), the wavenumber map is converted into the ET map shown in Fig. 3 (b). The true ET of the plate is thus recovered. Note the presence of diagonal lines in the shadowed region behind the defect, which are commonly observed with this post-processing technique and are due to a phase discontinuity induced by the defect [8].

![Figure 2](image1.png)

**Figure 2:** (a) A single frequency wavefield of the A0 mode “propagating” in a 2 mm aluminium plate obtained from a 3D FFT and subsequent filtering of one frequency slice at 150 kHz in wavenumber domain; (b) the corresponding FDIW map.

3. **Experimental results**

3.1. **Set-up**

The sample for the experiments is a 480 x 480 x 6 mm³ aluminium-CFRP composite plate built using resin transfer moulding process. The aluminium plate has the thickness of 2 mm and the CFRP plate of layup [0/90], is 4 mm in thickness. A drop weight impact tester (IM10, IMATEK) was used to impact the plate from the CFRP side at three different locations with the impact energies of 5, 10 and 30 J. The plate was impacted in its middle with the highest impact energy of 30 J which led to the buckling of the plate at the aluminium side. Two smaller impacts were performed left and right from the centre of the 30 J impact laying on the diagonal 70 mm away.

![Figure 3](image2.png)

**Figure 3:** (a) a FDIW map of a 2 mm aluminium plate with a 20 x 20 mm² “delamination” at the depth of 1 mm; (b) the resulting effective thickness map.

The sample was tested first using conventional ultrasonic pulse-echo method. The scan was performed from the CFRP side using a 4 MHz PZT transducer at a 0° incidence angle. The scan was centred on the middle of the sample and performed over an area of 240 x 240 mm² using a 1 mm step. For the analysis of guided waves, a 500 kHz broadband PZT transducer (Panametrics V101-RB Contact transducer, OLYMPUS) was glued 150 mm away from the location of the main impact. The excitation signal was a three-cycle burst at 150 kHz generated using a function generator (TG5011, AIM-TTI Instruments) and then amplified by a high-voltage amplifier (HVA-400-A, Ciprian) to 150 V before driving the transducer. The wavefield was recorded using a 3D scanning laser-Doppler vibrometer (PSV-500-3D-HV, Polytec). The scan area was approximately 200 x 200 mm² centred on the middle of the sample. Only the out-of-plane velocity components were used for the wavenumber mapping. At the chosen excitation frequency only S0- and A0-like modes...
exist. Since the composite plate is not symmetric with respect to the middle plane the modes cannot be separated into the antisymmetric and symmetric and only resemble S0 and A0 modes at this frequency.

3.2. Damage quantification

3.2.1. Conventional ultrasonic testing

The result from the conventional ultrasonic testing is shown in Fig. 4. This figure demonstrates an amplitude slice of the backwall echo (C-Scan) at the aluminium-CFRP interface. The delaminated area is clearly visible so that the size of the damage can be estimated and is equal to 164 x 175 mm$^2$. The weakest reflections come from the areas where the plate was impacted with the highest energies of 30 and 10 J, shown in Fig. 4 with dark blue colour (23 dB) in the middle and left corner of the delaminated area, respectively. This small amplitude is due to the shadowing effect coming from the numerous delaminations present between the transducer and the aluminium-CFRP interface. On the scan, there is no clear indication of the impact location with the lowest energy of 5 J, as in the case of other two impacts, see locations of the impacts marked with stars in Fig. 4. In the rest of the delaminated area the amplitude of the reflection is higher compared to the pristine region, see orange (62 dB) and green (58 dB) colours in Fig. 4, respectively. This is because in the pristine region, more of the wave energy is transmitted into the aluminium and less is reflected to the transducer.

![Figure 4: An amplitude slice of the backwall echo (C-Scan) at the aluminium-CFRP interface obtained using conventional ultrasonic pulse-echo method. Stars mark the impacts locations.](image)

3.2.2. FDIW-analysis from the CFRP side

Because of the asymmetry of the composite specimen two measurements were performed – one at the aluminium and one at the CFRP side. Thus, two models with respect to each side have to be considered to obtain the relationship between the thickness and the wavenumber. Using this relationship, the FDIW map can be converted to the ET map, which will indicate the delamination depth present in the sample. In the pristine region the ET is equal to the total thickness of the aluminium-CFRP composite plate. In the delaminated region the value of the ET corresponds to the depth at which the delamination is present and is smaller than the total thickness of the composite plate. Since delamination is likely to appear between the plies, the number of interfaces corresponds to the number of values for the ET. Thus, seven ETs are considered – six for each interface plus one for the pristine plate. The calculations in the SBFEM are performed for seven composite plates made of a single CFRP ply, two CFRP plies, etc. up to the total thickness of the aluminium-CFRP composite plate. Material parameters listed in Tables 1 and 2 were used for the calculations. The wavenumbers were taken for the A0-like mode at the frequency of 150 kHz due to its sensitivity to the thickness variation.

![Figure 5: Dispersion relation of the A0-like mode at 150 kHz as a function of the Effective Thickness: (a) complete non-monotonous relation (all thicknesses are considered) and (b) reduced monotonous relation. The different thicknesses are considered with respect to the CFRP side. Black lines show the wavenumbers obtained from the dispersion relation, whereas red lines show the interpolated wavenumbers.](image)
thickness pairs to achieve a monotonous relation. Thus, three wavenumber-thickness pairs were removed resulting in the reduced relation shown in Fig. 5 (b). The general trend now is that the wavenumber of the A0-like mode increases with the thickness reduction. The delamination closest to the scanned surface, which is at the CFRP side, will result in the higher wavenumbers.

Table 2: Material properties of a single transverse isotropic ply, where $C_{ij}$ are elastic constants and $\rho$ is density (where the direction 1 is along the fibres).

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<td>$C_{11}$</td>
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<td>$C_{12}$</td>
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<td>$C_{23}$</td>
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<td>GPa</td>
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<tr>
<td>$C_{55}$</td>
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<tr>
<td>$\rho$</td>
<td>1490</td>
<td>kg/m$^3$</td>
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Fig. 6 (a) shows the interactions of the S0- and A0-like modes with the impact damage measured at the CFRP side at a certain incident of time. The S0-like mode is faster, has bigger wavelength and lower amplitude than the A0-like mode. The S0-like mode passes the delamination region at the time of 64 $\mu$s, whereas the A0-like mode just arrives at the bottom edge of the delamination. The propagation of the S0-like mode over the delamination leads to a mode conversion to the A0-like mode. The converted mode scatters in all directions and highlights the delamination contour.

Fig. 7: (a) FDIW and (b) ET maps of the impact damage obtained from the experimental data measured from the CFRP side.

To obtain the FDIW map, a three-dimensional Fourier transform is applied to the measured wavefield data first. One slice is taken at the excitation frequency of 150 kHz and the S0-like mode is filtered out leaving the A0-like mode only. The resulting frequency slice is transformed using the inverse Fourier transform to retrieve a single frequency wavefield, which is shown in Fig. 6 (b). The IW algorithm is then applied to the single frequency wavefield and the resulting FDIW map is presented in Fig. 7 (a). While the impact damage is not observable in the single frequency wavefield in Fig. 6 (b), the FDIW map in Fig. 7 (a) clearly shows the size and shape of the damage. Uniform light blue colour is present in the pristine region, while green to orange colours highlight the delaminated region. The dispersion relation shown in Fig. 5 (b) is applied to the FDIW map to retrieve the ET map shown in Fig. 7 (b). The shape of the damage obtained from the guided wave-based FDIW analysis is in an excellent agreement with the one from the conventional ultrasonic testing, to be seen in Figs. 7 (b) and 4 respectively. The ET map estimates correctly the total thickness of the plate in the
pristine region, see yellow colour for the thickness of 6 mm in Fig. 7 (b). For the whole delaminated region green, blue and orange colours are present, corresponding to the thickness values around 4, 2 and 5 mm, respectively. The biggest delaminated region is at the aluminium-CFRP interface visible in Fig. 4, thus the expected value for the ET should be 4 mm which correlates with the estimate obtained from the ET map, see green colour in Fig. 7 (b). Also, the ET map indicates delaminations which lie closer to the surface of the CFRP for the ET values between 1.34 and 2.68 mm, shown with blue colour in the middle and left corner of the delaminated region in Fig. 7 (b). These values of 1.34 and 2.68 mm correspond to the delamination positions between 2nd and 3rd ply, and 4th and 5th ply, respectively. Other positions, for instance between the 1st and 2nd ply, 3rd and 4th ply, and 5th and 6th ply, are not possible to estimate, since the reduced relation is used. Probably due to that there is orange colour visible in the damaged region, corresponding to the ET of approx. 5 mm. Another reason maybe that not the whole region is delaminated homogeneously and still plies and the aluminium plate in some regions are connected. This leads to the ET value close to the total thickness of the aluminium-CFRP composite plate.

The resulting size of the impact damage estimated from the FDIW analysis is 160 x 184 mm², see Fig. 8. The estimate is in a good agreement with the values obtained from the conventional ultrasonic testing (see Fig. 4). The FDIW analysis slightly underestimates the damage size in one direction and overestimates it in another one, which is the direction of the incidence wave.

3.2.3. **FDIW-analysis from the aluminium side**

The result from the conventional ultrasonic testing shown in Fig. 4 demonstrates that the biggest delamination is at the aluminium-CFRP interface. Thus, this delamination will hide all other smaller delaminations in the CFRP part when measured from the aluminium side due to the shadowing effect. However, it simplifies the model with respect to the aluminium side. Only two effective thicknesses and therefore two wavenumbers are considered – one of 576 rad/m for the 6 mm pristine aluminium-CFRP composite plate and another of 610 rad/m for the 2 mm aluminium plate delaminated from the rest of the composite plate.

The same process as described in the subsection “FDIW-analysis from the CFRP side” is used to analyse the experimental wavefields. The resulting FDIW and ET maps are in Fig. 9 (a) & (b), respectively. It is not possible to clearly identify the shape of the damage from both maps as in the case of the analysis performed from the CFRP side, (confer Figs. 9 and 7). The ET map for the measurements performed on the aluminium side shows that aluminium is delaminated from the CFRP in most of the area scanned, shown with blue colour in Fig. 9 (b). The poor result with respect to the aluminium side probably comes from the measurement noise and the close relation between wavenumbers for the pristine composite and aluminium plate – 576 and 610 rad/m, respectively. Also, as it was already mentioned, maybe not the whole region is delaminated homogeneously and that the aluminium plate is still in contact with the CFRP plies in some regions.

The wavenumber imaging technique was successfully applied to a delaminated aluminium-CFRP composite structure which corresponds to composite-

![Figure 8: Damage map obtained from the guided wave-based FDIW analysis.](image)

![Figure 9: (a) FDIW and (b) ET maps of the impact damage obtained from the experimental data measured on the aluminium side.](image)

4. **Conclusion**

In this contribution, the wavenumber imaging technique was successfully applied to a delaminated aluminium-CFRP composite structure which corresponds to composite-
overwrapped pressure vessels used for storing gases in aerospace and automotive industries. The output of the imaging is a three-dimensional representation of the delamination induced by the impact. The damage quantification results from the FDIW are in a good agreement with the results from conventional ultrasonic testing. The main limitation of the approach presented here is that it is not possible to quantify every delamination position across the thickness to the non-monotonous relation between the wavenumbers and effective thickness. This limitation comes from the layup of the composite plate used in the experiments.

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