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Identification of impact damage in sandwich composites by acoustic camera detection of leaky Lamb wave mode conversions

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Abstract
The present feasibility study demonstrates that impact damage in a sandwich composite can be identified by mapping the interaction of Lamb waves with the damage-induced structural heterogeneity. By inducing mode conversion of the fast Lamb mode, S₀, into the slow mode, A₀, the damage site acts as a secondary acoustic source of airborne ultrasound, which can be detected by an acoustic camera. This irradiation is finally enabled by the polarisation of the particle displacements in the A₀ mode which is oriented perpendicular to the plate surface at low ultrasonic frequencies.

Keywords: Acoustic camera, mode conversion, Lamb waves, impact damage, sandwich composite

1. Introduction

Non-destructive testing (NDT) using ultrasonic waves is being widely applied for diverse maintenance operations in engineering structures. The approach allows to detect cracks, thickness variations resulting from abrasion or erosion, as well as flaws in welded joints. Adapted implementations of ultrasonic NDT are available for many different kinds of materials, including metals and polymers [1]. Driven by recent developments, especially in aerospace applications, also ultrasonic detection of defects in composite materials has attracted much attention [2-4]. In particular the use of ultrasonic C-scans has become a standard for the qualification of the respective materials in production and in maintenance operations [5]. One of the main goals in NDT research is to develop techniques that allow detection of “barely visible impact damage (BVID)” [6] in composite parts. BVID often remains unnoticed by visual inspection, but in spite of the surface of the material being barely affected, while the inner core already shows a serious degree of degradation.

In many practical applications, ultrasonic waves are excited and received by piezoceramic transducers. However, due to the waves leaking into the surrounding air, also standard electret microphones can be used to detect their airborne components, especially for case where the frequencies are not too far from the audible range [7]. Acoustic cameras, equipped with such microphones, are already frequently being applied to visualise noise sources in different engineering structures. Their wide applicability make them an ideal tool in acoustic research [8,9]. Acoustic cameras, equipped with such microphones, are already frequently being applied to visualise noise sources in different engineering structures. Their wide applicability make them an ideal tool in acoustic research [8,9].

Due to their confinement in a 2D plate structure, Lamb waves can propagate over longer ranges than bulk waves, up to tens or even hundreds of meters, so that they are well-suited for long range inspections [10,11]. In non-bended structures and at low frequencies, there exist only two types of Lamb waves, classified as the symmetric and the anti-symmetric mode,
involving particle motion symmetric and antisymmetric around the midplane, respectively. With increasing frequency, higher-order Lamb propagating modes emerge. The detection of material damage by monitoring Lamb wave propagation is based on the disturbance of the wave propagation by heterogeneities induced by material degradation, such as corrosion, cracking or delamination. When a Lamb wave of a certain mode encounters a heterogeneity, it is partially reflected, and converted to other Lamb modes (Figure 1).

![Figure 1 Principle of defect detection using Lamb waves, a) incident wave, b) reflected and transmitted wave. Note that in this example sender/receiver and defect are situated at opposite sides of the plate.](image)

Lamb wave detection can be implemented in an active or passive operation mode: In the active mode of operation, a selected type of Lamb wave is generated by an actuator, and the information about the damage state is derived from observed reflected/transmitted/mode converted waves [12]. In the passive mode of operation, Lamb waves are generated during the formation or agitation of damage by natural mechanisms. Online detection is needed here by suitable sensors. This approach comprises modal acoustic emission [13,14].

In this paper, we verify the feasibility of exciting Lamb waves in a sandwich composite, and detecting mode conversion by use of an acoustic camera. Our goal is to avoid time consuming airborne ultrasonic scanning, by using a snap-hot method that can save essential inspection time, by recording and processing raw data in just a couple of seconds. The envisaged approach is intended to be complementary to other ultrasonic NDT methods, in a scheme of first identifying suspicious defect areas in large inspection regions by the acoustic camera, and then inspect these in detail by an ultrasonic C-scan, shearography, or thermography. The pre-requisite is that Lamb waves are efficiently excited by e.g. embedded piezoceramic actuators [15]. Those embedded actuators could optionally even serve as online-impact detecting devices (acoustic emission). In this sense, the proposed technology would make a bridge between classic NDT and structural health monitoring (SHM).

2. Materials and Methods

2.1 Composite samples
The materials under investigation were: a part of a helicopter tail-boom (EC 135) and a demonstrator plate. Both samples were constructed as a carbon fibre reinforced plastic (CFRP) sandwich composite with a honeycomb core having a thickness of 15 mm. The tail boom part was bended, and it only had a monolithic skin on the outside (1 mm). The demonstrator plate was flat and had a monolithic skin on both sides. The EC 135 tail boom has already been a subject of intense research [7, 16] and its acoustical properties have been well characterized.
2.2 LASER-DOPPLER Vibrometry
Laser Doppler Vibrometry (LDV) has already been used for damage detection in aircraft parts such as panels and fuselages [17]. LDV was also proposed for the investigation of acoustic nonlinearity in delaminations of composite materials of aircrafts, and for modal testing and analysis. By using dedicated scanning facilities, LDV provides images of the Lamb wave surface displacement field at different instants after excitation. Here we have used LDV for determining the degree of symmetry of the acoustic displacements at both sides of the tail boom. A Laser Doppler interferometer (Polytec OFV 353), in combination with an OFV 3001 controller was used. Lamb waves were excited using a piezoceramic patch that was adhesively attached at the inner surface of the tail boom demonstrator. In Figure 2, one can clearly see the laser illuminated area at different measuring points. Also displacements at the edges of the sandwich panel were detected (data not shown).

![Figure 2 Set-up for determining the acoustic response to piezo-electric excitation at opposite positions of a composite plate sample. Left: inner side of the tail boom with reflecting tape; middle and right: laser spot at the inside and outside of the tail boom at the same location.](image)

2.3 Excitation of Lamb waves
Both composite samples were equipped with a rectangular PZT that served as an excitation source for Lamb waves. The PZT, obtained from PIEZOCERAM, S.R.O., Czech Republic, had a rectangular shape with 5 cm in length and 1 cm width (Figure 3). Given the low excitation frequency (and therefore long wavelength) of interest, the transducer was used in a non-resonant mode. Lamb waves were excited using a PZT patch that was attached to the composite by an aircraft-certified epoxy adhesive (Loctite Hysol EA 9309.3NA). A high power acoustic amplifier was used (HQ Power Professional Audio Amplifier), amplifying bursts generated by an Agilent 332550A function generator. Single bursts, with a duration of 5 cycles, turned out to be sufficient to record acoustic images with good signal to noise ratio.

2.4 Air-coupled ultrasonic technique for Lamb wave visualisation
In order to visualise the Lamb waves interacting with the impact damage, the honeycomb composite plate sample was scanned using an adapted air-coupled ultrasonic equipment [18]. The position of the barely visible impact damage that was induced by a hammer drop is indicated by a coin (2 Euro). The C-scan facility used was a USPC 4000 AirTech system (Ingenieurbüro Dr. Hillger) equipped with an air-coupled transducer for scanning the composite plate with a grid size of 1 mm with a full-wave data recording. The data files contain the whole information of the wave about the wave propagation and all interactions.
2.5 Acoustic Camera

A 48-channel ring array (75cm) covering the sound intensity range between 35 dB and 130 dB was used to detect signals between 400 Hz and 25 kHz. The typical single map dynamic range was around 7-8 dB, but can be amplified via special algorithms (High Dynamic Range - HDR - Algorithm). The measurement distance in the present configuration could be chosen between 0.5 and 5 m, but larger distances are possible depending on the environment and signal strength. The microphones were mounted on a carbon fibre ring. The specially designed microphone cards sampled each channel operating at a sampling frequency (parallel sampling) of 192 kHz using a 24bit AD converter. The data were A-weighted, and the focus of this analysis was on frequencies around 22 kHz. The acoustic preconditions of the room in which the measurements were taken were by far not ideal. In this way they already represent quite realistic conditions for a final application, such as in a hangar of an airport.

3 Results and Discussions

3.1 Determination of the optimum detection frequency for Lamb waves
For the detection of impact damage essentially situated in the core of a plate, the displacement field of the probing waves should cover its complete cross-section [19] (Figure 1). In order to verify this, preliminary tests were performed investigating the acoustic displacements at both sides of the composite, while exciting the structure on one of its sides.
Figure 5 Selected waveforms recorded for different excitation frequencies (8; 15 and 22 kHz, from top to the bottom) registered outside and inside the tail boom demonstrator. The time axis is in units of microseconds, while the other axis represents the output voltage of the vibrometer (in arbitrary units). For all three frequencies the amplitude and the shape of the waveforms remain approximately equal with respect to identical positions at both sides of the plate, confirming the (anti-)symmetrical nature of the detected wave modes.

Figure 5 shows selected waveforms detected at opposite sides of the sandwich composite. In contrast to the monolithic CFRP skin being present only at the outside of the tail boom demonstrator, not at the inside, the waveforms inside and outside the tail boom, that were determined exactly at the same position in the x-y plane show similar shapes and amplitudes. All the results together finally prove that up to a frequency of approximately 30 kHz, the waveforms propagate symmetrically at both sides of the composite material. Furthermore, the bursts become faster with increasing frequency, indicating a dominating \( A_0 \) mode.

### 3.2 Visualisation of the Lamb wave propagation and mode conversion

Figure 6 visualises a snapshot of the propagation of Lamb waves using ultrasonic inspection along the composite plate at \( t=204 \ \mu s \) after the initial burst was launched (middle and right). From a corresponding B-scan (left), the group velocities of the respective wave modes were determined to be 4000 m/s and 550 m/s, corresponding to wavelengths of 18 cm and 2.5 cm. The slower (presumed \( A_0 \)) mode can clearly be identified by its short wavelength. The group velocity of the \( A_0 \) mode lies close to the speed of sound in air.
At the selected time, $t=204 \, \mu s$, the initial $S_0$ wave was already reflected at the plate edges and at the impact damage itself (right picture) leading to a superposition of the initial $A_0$ wave with the mode-converted $A_0$ reflections from the incident $S_0$ mode (see also below). The impact damage is thus behaving as a secondary source of sound, nicely illustrating the Huygens principle. The complexity of the emerging interference patterns also emphasises why 2D imaging methods are crucial in order to reliably analyse the interaction of Lamb waves with defects in confined plate structures.

Mode conversion [2] from the $S_0$ mode into the $A_0$ mode (Figure 7) occurring at “symmetry-breaking” discontinuities, such as defects and plate edges [7] is essential for the proposed technology. In Figure 6, the $A_0$ mode is more visible than the $S_0$ mode because of the polarization of the particle displacements being respectively normal and tangential (Figure 7). Based on the results in 3.1 (suitability of the low ultrasonic frequency) and 3.2 (detection of airborne ultrasound and mode conversion into $A_0$ modes at defects), it was hypothesized that damage from impacts could easily be identified by an acoustic camera. The use of leaky Lamb waves, i.e. Lamb waves that release acoustic energy into the surrounding air, for non-destructive testing of composites, was already proposed in the literature [2,20]. In the next
section, we verify up to what extent the leaked waves can be mapped by means of an acoustic camera.

3.3 Visualisation of the impact damage using the acoustic camera

The pictures provided by the acoustic camera are usually composed of an optical image overlaid by the corresponding acoustic image. Parts of the raw waveforms can be displayed for diverse positions, and further analysis tools, such as frequency filtering or “source removal” (via a Software tool called Acoustic Eraser), are available. In Figure 8, the optical image shows the composite plate deposited on a scaffold. The PZT patch is positioned at the top of the plate and connected to the amplifier and the wave generator. Various wave bursts were generated and one of those bursts was finally recorded with the acoustic camera.

![Figure 8 Visualisation of the burst excitation. The waveform above represents the sound field inside the encircled area (defect position).](image)

Figure 8 shows an “Acoustic Photo” obtained for the time frame indicated in the respective waveform. At this stage, no additional processing, such as frequency filtering was applied. One clearly sees the interference patterns exceeding the plate edges, demonstrating that really ultrasound in air is visualised. On the basis of the known dimensions of the picture, the wavelength appears to be in the range of 1 to 2 cm, corresponding to a frequency of 22 kHz and an assumed sound velocity in air of 330 m/s. The ringing of the acoustic source is still visible, even exceeding the signal from the impact damage that appears as a faint point in the middle of the plate. The position of the impact damage is encircled and the corresponding waveform for this area is shown at the top of the screenshot.
In Figure 9, the acoustic photo was obtained for a narrow frequency band around 22 kHz. An amplitude threshold was applied so that only signals with pre-defined amplitude are displayed. The intensity in the previous picture was normalised against the strong excitation signal and the damage signal could not be distinguished from other signals arising from e.g. constructive interference patterns. Therefore, for improved damage identification, further processing is needed.

Figure 10 Defect visualisation when source is removed from the picture by the imaging software. The spectrum with a linear scale is indicated at the right side.
This is e.g. possible by setting a time gate at a sufficient time after the initial burst, so that the damage gets the required contrast to become distinguishable from artefacts. In the present instrument, there is a corresponding software tool available enabling the extraction of sound sources. Another simple option would be to allow saturation of the excitation source and to limit the dynamic range accordingly in order to increase the resolution for differentiating defect signals from the background.

The acoustic photo in Figure 10 was composed using the time-gated signals and an adapted frequency band that is illustrated at the right side of the screenshot. Now, by neglecting the source, the impact damage is the “loudest point” in the acoustic photo clearly exceeding the intensity of the artefacts that arise from constructive interferences.

As motivated above, due to the mode conversion from the $S_0$ into the $A_0$ mode, the composite plate generates airborne ultrasound preferentially at the position of the defects. This is analogous to various non-linear effects that also behave as sound sources. However, in our case, not non-linearity but mode conversion of Lamb waves is exploited. In the next figure, the pictures obtained from the air-coupled ultrasonic technique and the acoustic camera are superimposed illustrating the full potential of the method.

![Figure 10](image1.jpg)

**Figure 11** Superposition (right picture) of cut-out pictures taken from Figure 6 (left – Lamb wave propagation) and Figure 10 (middle- acoustic picture) showing the usability of the acoustic camera to identify defects using ultrasonic Lamb wave conversion.

Key questions, which will be answered in a subsequent study, concern the smallest detectable impact damage, as well as the maximum distance between investigated object and acoustic camera. What we already know is that the contrast of the damage signal is similar to the contrast from Lamb wave visualisations obtained by air-coupled ultrasonic technique; so we can be optimistic that the final performance will also be similar, i.e. critical impact damages (7) can most probably also be detected by the acoustic camera. In further tests, also the beam characteristics of the “sounding defect” will be analysed. This will decide on the possible position of the acoustic camera, such as an inclined position, as well as the requirements when using bended structures.

To distinguish between real defects and artefacts arising from constructive interference patterns, the acoustic pictures can also be recorded for different frequencies or even using a frequency sweep. Moreover, different sound sources should be used to enhance the contrast of the damage signal with respect to potential artefacts. This is also important because of the dependence of the respective position of the defect with respect to the source. Without absorption, the acoustic amplitude decays with $1/r$ of the distance from a point source, and this distance has to be considered when damage sizes are estimated.
By triggering the acoustic camera with repeated bursts from the sound source, the signal-to-noise ratio (SNR) can essentially be improved by accumulating signals because in the present case, only one shot was analysed. It is however also possible via the software to mark several bursts in the time domain and displaying it on one “Acoustic Photo”.

4 Conclusions and Outlook
The obtained images clearly demonstrate the feasibility to detect impact damage using the acoustic camera when a Lamb wave was launched into the plate structure before. It has to be emphasised that only one burst was recorded and the corresponding processing time lies in the range of just a few seconds. The applied signal processing using frequency filtering and “source removal” is straightforward and does not require free parameters to be obtained by calibration procedures. Finally, the technique appears to be applicable to all defects that create characteristic mode conversions where the resulting particle displacement has a dominating component that is perpendicular polarised to the plate surface ($A_0$ mode).

Despite of the very encouraging results, there are many options to improve the detection capabilities, such as the accumulation of wave forms. The applicability of the system for more complex or bended objects needs to be further investigated to fully exploit the possibilities of that technology. It would also be interesting to compare the acoustic images obtained from different embedded sound sources. The same holds for a variation of excitation frequencies to finally enhance the reliability of the defect detection. Given the short processing time, the analysis of images from different sources of frequencies would also not be a limiting factor.

Last but not least, when tailored acoustic cameras could be produced at a lower price by only focusing on limited features unlike for a multi-purpose camera, a cheap alternative to some other techniques could be established, and especially visual inspections could be facilitated.

In a final application, a composite fuselage panel could contain an array of embedded low-end piezoceramic actuators that enable damage detection using an acoustic camera. In this way, NDT and SHM would be coupled enabling a combination of the positive aspects of both approaches, i.e. the high-end reading out technology would remain mobile and upgradable whereas the durably embedded actuating devices remain low-end benefiting from their inherent robustness.

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