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## **Detection of barely visible impact damage in composite plates using non-linear pump-probe technique**

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### **Abstract**

In the last decades, composite materials have been increasingly used in aircraft structures as a mean to reduce the weight. For safety reasons, periodic checks of impact-induced damage need to be performed. In that framework, ultrasound non destructive testing has proven its ability to detect macro-defects such as delamination. However, at early stages, Barely Visible Impact Damage (BVID) may not be detected via linear ultrasound techniques. In recent years, non-linear ultrasound has gained traction for the inspection of such defects. However, detection of the weak non-linear defect signature buried in ambient noise remains challenging, and depends on an empirical choice of excitation frequencies.

This study focuses on the evaluation of a non-linear pump probe ultrasound inspection technique applied to BVID in multilayer carbon fibre reinforced composites used in aeronautics. In particular, the influence of various experimental parameters on the measured non-linear response is studied.

A low frequency pump wave (via a shaker) and a high frequency wave (via a piezoelectric transducer) are transmitted to the medium while a second transducer records the ultrasonic response. Both pump and probe waves are sent in the form of a few seconds-long frequency sweep, in the audible and ultrasonic range respectively. Appropriate post processing is then applied to the recorded signals to retrieve the non-linear response of the defect. The procedure is repeated on several composite plates with and without impact damages. The nonlinear response appears in the form of modulation sidebands in the frequency spectrum of the post-processed signals. The relative amplitudes of the side bands obtained for the various samples with various defect sizes and excitation amplitude or frequency content are studied. Optimal experimental parameters were obtained and led to a good detection of defects. The limits of the method are also discussed.

**KEYWORDS:** Non-destructive testing, composite, non-linear ultrasound, pump-probe experiment

### **1. Introduction**

The present paper aims at detecting barely visible impact damage (BVID) in composite plate-like components for aeronautic applications. While classical linear ultrasound

techniques are commonly used to detect cracks or delamination [1], they may fail to detect early stage defects. In recent years, non-linear ultrasound has gained traction for the inspection of such defects through the activation of Contact Acoustic Nonlinearity (CAN) [2]. Among them, pump-probe techniques are advantageously less sensitive to electronic non-linearity than second-harmonic based non-linear techniques. However, in most papers, the choice of an optimal combination of low and high frequency excitation is empirical; as shown by [3], it depends on the defect shape and depth as well as the material characteristics. Dzieciech et al [4] proposed an alternative technique based on the adaptively resampling of the signals measured with a vibrometer after simultaneous low and high frequencies chirp excitations. They could detect nonlinearity induced by fatigue crack in an aluminium beam.

In this paper, pump-probe experiments are conducted on a set of identical Carbon-Fiber Reinforced Plastic (CFRP) plates with or without BVID, using lightweight piezo-electric wafer active sensors (PWAS) [5] for both probe and sensing. Experimental parameters are optimized through a parametric study, and results are compared to classical linear DAS imaging. Lastly, the limits of the method are discussed.

## 2. Materials and Methods

### 2.1 Samples

Pump-probe experiments are conducted on five identical 400mm x 400mm x 2.2mm laminate carbon-fiber reinforced composite plates. Four of them are submitted to an impact using a drop-tower to induce early stage delamination at different positions, see table 1. The delamination diameter was determined using 5MHz frequency immersion scanning and confirmed with Infra Red Thermography.

**Table 1. BVID parameters of the four impacted composite plates.**

Sample reference	Impact energy [J]	Indentation depth [mm]	Impact position [mm × mm]	Delamination diameter [mm]
E1	4	0.1	(200, 200)	14
E2	5	0.15	(200, 200)	16
E3	5	0.17	(200, 200)	15
E4	5	0.14	(250, 150)	16

### 2.2 Pump-probe experiment

#### 2.2.1 Experimental set-up

A 10mm-diameter Steminc PWAS bonded to the plate transmits a high frequency chirp typically ranging from [30-240] kHz for 10 seconds. Simultaneously, a B&K 4809 shaker attached to the plate vibrates following a chirp with the same chirp rate (typically [0.25-2] kHz), also for 10 seconds. Meanwhile, a second 10mm diameter PWAS bonded to the plate measures the propagated waves with a 1MHz sampling frequency, see figure 1.

The raw signals are post-processed using python software. Firstly, they are over-sampled to 4MHz, then submitted to the same adaptive resampling procedure proposed by Dzedziech et al [4]. Basically resampling is performed with a linearly decreasing time step (with the same rate as the chirp rate) so as to transform a frequency-increasing linear chirp into a sinus wave. Each linear chirp present in the raw signals then appears as a short peak in the spectrum of the adaptively resampled signals, enabling the extraction of side-band peaks for non-linear response detection.

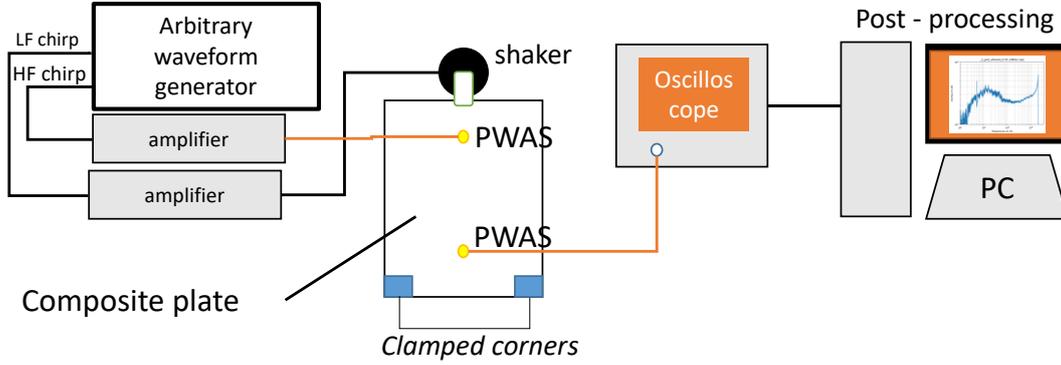


Figure 1. Experimental set-up

### 2.2.2 Computation of non-linear index

A non-linear index is defined as the sum of all side bands peak amplitudes above the noise level in the adaptively resampled spectrum (equation 1).

$$R = 20 \log_{10} \left( \frac{\sum_{i=1}^N A(F_{Si})}{A(F_{HF})} \right) \quad (1)$$

With  $A(F_{Si})$  the amplitude of the  $i$ th side band peak,  $A(F_{HF})$  the amplitude of the high frequency peak and  $N$  the number of modulation side bands.

## 3. Results and discussion

### 3.2 Influential parameters

Particular attention was given to the choice of PWAS. Experiments showed that the first resonant frequency (radial mode) of the bonded PWAS must not overlap with the useful frequency range of the pump-probe experiment to avoid undesirable non-linear phenomenon. The first resonant frequency of the PWAS used in this paper was greater than 300kHz.

A parametric study was conducted on all plates to determine the influence of the excitation amplitudes on sidebands in the resampled spectrum. As expected, the higher the pump excitation, the higher the sidebands (thus  $R$  increases), see figure 2 on the left. Note that weak modulation side bands could be detected on the pristine plate in this configuration, due to the non-perfect clamping conditions at the corners of the plate that lead to nonlinear contact defect. However, these side bands peaks are significantly weaker for the pristine plate than for the damaged plates, which proves the efficacy of the technique to detect early impact damage in composite plates.

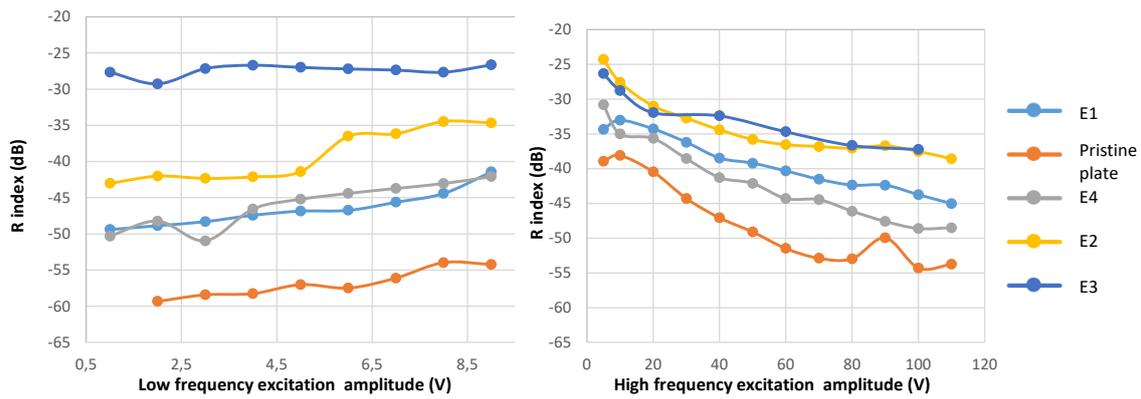


Figure 2. Nonlinear index R obtained with pump-probe experiments on the 5 CFRP plates with increasing pump amplitude (top) or increasing probe amplitude (bottom).

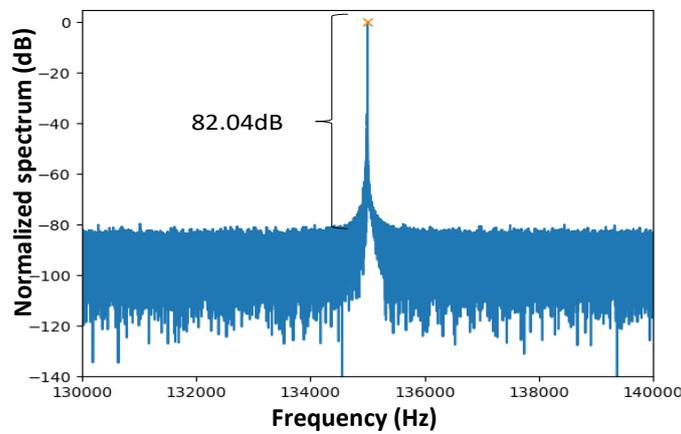


Figure 3. Spectrum of adaptively resampled signal measured on pristine CFRP plate, optimal configuration.

Table 2. Non-linear side band index (R) and noise level measured on the 5 CFRP plates.

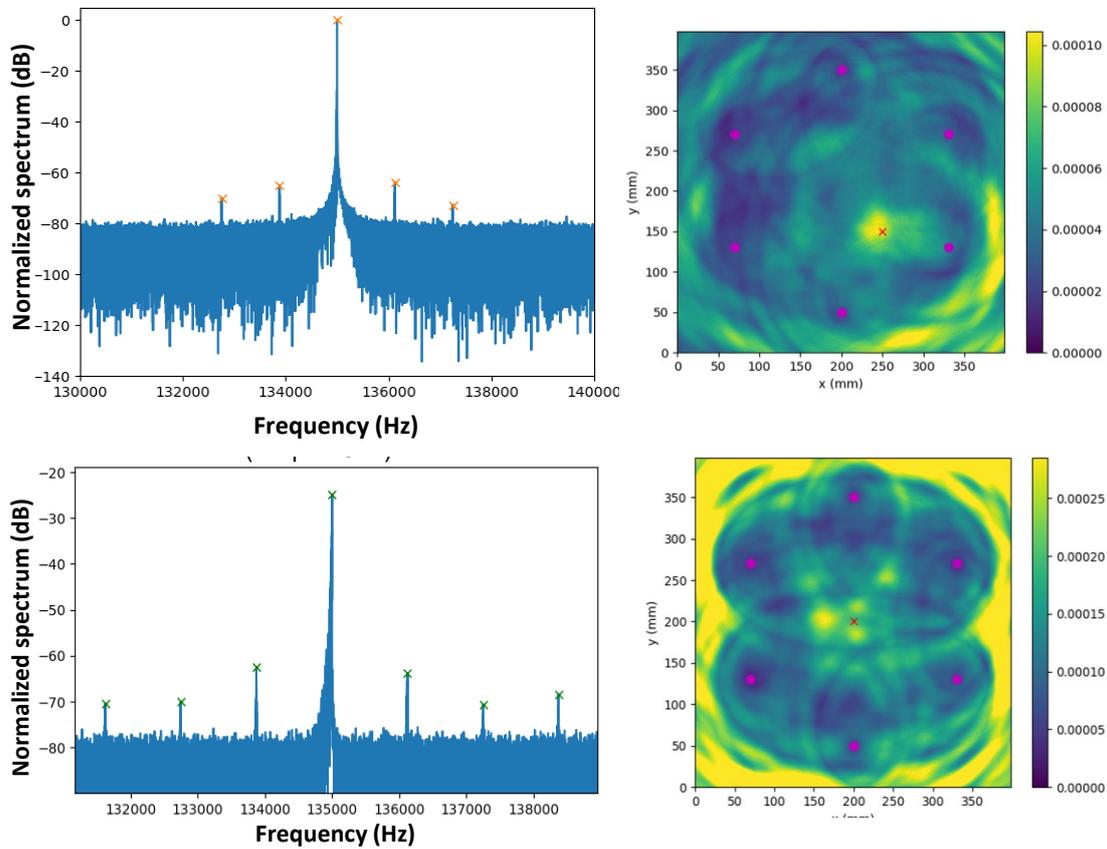
	R (dB)	High frequency peak amplitude/noise level (dB)	Noise level (dB)
Pristine plate	<b>No side bands above noise</b>	<b>82.0</b>	<b>-82.0</b>
E1	<b>-59.5</b>	<b>78.9</b>	<b>-78.9</b>
E2	<b>-46,0</b>	<b>68.0</b>	<b>-68.0</b>
E3	<b>-25.4</b>	<b>50.8</b>	<b>-75.6</b>
E4	<b>-53.6</b>	<b>78.6</b>	<b>-78.6</b>

Similarly, the influence of the probe amplitude or the ratio between low frequency and high frequency excitation on the non-linear index R was studied. In all cases, the R index was lower for the pristine plate than for the damaged ones. An increase in probe amplitude seemed correlated with a decrease in the R modulation index (figure 2 on the right), which needs to be further investigated.

The optimal experimental parameters were found to be an excitation voltage amplitude of 3V for the shaker and 50Vpp for the PWAS probe; the ratio between instantaneous transmitted high frequency and low frequency was 120, and the chirp duration was 10s. Figure 3 displays the adaptively resampled spectrum measured on the pristine plate in this configuration. No side bands could be detected above the noise level. Table 2 sums up the R index computed on the five plates in this case, as well as the noise level in the spectrum of the resampled signals.

### 3.3 Comparison with linear inspection method (DAS imaging) and discussion

Linear DAS images [6] were computed from measurements of transmitted qA0 Lamb waves with six 18mm-diameter PWAS bonded to the plates, transmitting 40 kHz tonebursts. While the BVID of plate E4 is detected and its location is correct, the image of BVID of plate E3 is too noisy for proper detection. The pump probe method is able to detect both defects via their nonlinear response.



**Figure 4.** On the left, spectrum of adaptively resampled signal measured on impacted plate (top: E4 plate, bottom : E3). On the right, DAS images computed using linear Lamb waves with 6 PWAS (located on the rosa dots, on the right). The BVID true location is indicated by a red cross.

Nevertheless, while the simultaneous excitation of high-frequency and low-frequency chirps combined with the adaptive resampling post-processing efficiently detects CAN defects, it is not suited to locate defects using classical imaging algorithms. The width of the sidebands in the spectrum of adaptively resampled signals increases when the chirp duration decreases, to the point where they begin to overlap with the high frequency peak. In our configuration, the chirp needed to be longer than 3 s for sidebands to be

distinguished. This is not compatible with typical DAS imaging where short time signals are needed to avoid overlapping of reflexions on the specimen edges with direct ultrasound path. Other strategies could be considered such as spatial focusing of pump energy [7] or model-based inversion to locate the defects.

## 4. Conclusions

In this paper, BVID were inspected using a pump-probe technique with simultaneous transmission of low and high frequency 10s-long chirps using a shaker and PWAS respectively. BVID were introduced with a drop-tower impact on four CFRP composite plates. A non-linear index R was computed using side band peak detection in the spectrum of the adaptively resampled signals. Experimental parameters were optimized via a parametric study. It was found that this index allows a good detection of the four BVID, while linear DAS imaging was not able to detect all of them. Further work will focus on developing an imaging algorithm compatible with this technique, i.e. with the simultaneous transmission of two long chirps.

## Acknowledgements

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