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Investigation to Local Defect Resonance for Non-Destructive Testing of Composites †

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† Presented at the 18th International Conference on Experimental Mechanics, Brussels, Belgium, 1–5 July 2018.

Published: 27 May 2018

Abstract: Local defect resonance (LDR) makes use of high frequency vibrations to get a localized resonant activation of a defective region. In this study, the LDR behavior of carbon fiber reinforced polymer (CFRP) coupons with three different types of damages is investigated using broadband measurements obtained with a scanning laser Doppler vibrometer (SLDV). First, the LDR response of flat bottom holes of different depths and sizes is evaluated using a signal-to-noise ratio. Next, results are obtained for ETFE inserts where the difference between (artificial) delaminations and inserts is outlined. At last, the vibrational response of a CFRP coupon with barely visible impact damage is investigated. This type of damage has a more complex structure, and it is shown that frequency band data (an alternative to the single frequency LDR) performs well in identifying such complex damage.

Keywords: local defect resonance (LDR); Frequency Band Data (FBD); non-destructive testing (NDT); composite materials; Laser Doppler Vibrometry (LDV)

1. Introduction

Composite materials (e.g., carbon fiber reinforced polymer (CFRP)) are widely used in many advanced engineering structures. Their high specific strength and resistance to fatigue and corrosion makes them especially attractive for transportation applications. A concern in the use of composite materials is related to the occurrence of and sensitivity to internal damage features. The damages are often invisible to the naked eye e.g., barely visible impact damage (BVID). Of utmost importance is a non-destructive testing (NDT) technique that can be used to detect and evaluate small damages.

In 1993, Tenek et al. [1] proposed NDT of composite plates by high frequency modal testing. This technique was further investigated by Solodov et al. [2,3] during the past decade. These high frequencies are used to get a localized resonant activation of the defected zones and is therefore named: Local Defect Resonance (LDR). In general, the defect's location is revealed by measuring the out-of-plane surface response of a defected sample using a scanning laser Doppler vibrometer (SLDV).

In the present study, the performance of LDR as a NDT technique is experimentally evaluated for three different types of artificial defects in CFRP coupons, namely: flat bottom holes (FBHs), ethylene tetrafluoroethylene (ETFE) inserts and BVID.

2. Materials and Methods

Three different types of artificial defects are investigated. For each type of defect, one or more test specimens are manufactured. The first type of defect is a circular FBH for which three different CFRP 150 × 90 × 5.52 mm^3 samples are manufactured with layup $[(45/0/–45/90)]_{3s}$. In each of these three coupons, five circular FBHs are machined with variable depths and with diameters of 10, 15 and 20 mm. The second defect type is an insert. The inserts are made from ethylene tetrafluoroethylene (ETFE) plastic with a nominal thickness of 12 µm. ETFE is a fluorine-based plastic such as polytetrafluoroethylene (PTFE, Teflon). The plastic film is folded over itself to create square 20 × 20 × 0.06 mm^3 pockets. The low stick polymer type and pocket like design of the inserts aim to create defects which behave as delaminations. The inserts are placed between consecutive layers of a 150 × 150 × 2.6 mm^3 CFRP plate with layup $[(0/90)_2/0]_s$. The third and last type of damage is BVID. A 150 × 100 × 5.5 mm^3 CFRP coupon with layup $[(45/0/–45/90]_{3s}$ is impacted with a 7.72 kg drop-weight with 16 mm impactor-tip according to the ASTM D7136. The measured impact energy is 6.3 J, and introduced BVID.

All samples are suspended using elastic bands and excited using low power piezoelectric (PZT) patches (type EPZ-20MS64W from Ekulit, with a diameter of 15 mm) glued to the surface (see Figures 1c, 2d and 3. A burst chirp signal (i.e., fast swept sine followed by a zero signal for 10% of the total signal length) is used as excitation signal. This signal is amplified 50 times by a Falco System WMA-300 amplifier to increase the energy input. The in-plane and out-of-plane vibrational response is obtained using a 3D infrared scanning laser Doppler vibrometer (Polytec PSV-500-3D XTRA). Orthogonal projection is used to calculate the velocity of vibration in the X, Y and Z directions, where Z is defined as the out-of-plane component. Only the out-of-plane velocity component is used in this investigation. Though note that the LDR phenomena equally exists in the in-plane directions [4]. Table 1 summarizes the measurement settings used for the different scans.

Table 1. LDV measurement settings.

	FBH Ø10	FBH Ø15	FBH Ø20	Inserts	BVID
# **Scan points**	5225	1861	2967	2915	2847
Scan point spacing (mm)	1.4	2.2	2	2.5	2
f_{min} **(kHz)**	5	5	5	5	2
f_{max} **(kHz)**	100	80	100	80	100
Frequency resolution (Hz)	31.25	25	31.25	25	62.5
V_{pp} **(V)**	100	50	100	50	100

3. Processing Measurement Data

The measured velocity data at each scan point is imported to Matlab. The fast Fourier transformation (FFT) is performed to process the dataset in the frequency domain. In this study, a signal-to-noise ratio SNR is used to investigate the sensitivity of LDR. The SNR can be calculate at each frequency as:

$$\mathrm{SNR}(f) = \frac{\frac{1}{n_{defect}}\sum_{(x_i,y_i)\in\Omega_{defect}}\left(\frac{V_k(x_i,y_i,f)}{U_{ref}(f)}\right) - \frac{1}{n-n_{defect}}\sum_{(x_i,y_i)\notin\Omega_{defect}}\left(\frac{V_k(x_i,y_i,f)}{U_{ref}(f)}\right)}{\sigma(f)_{(x,y)\notin\Omega}} \quad (1)$$

where n is the total number of grid points, n_{defect} is the number of grid points inside the known damaged area (Ω_{defect}), $V_z(x_i,y_i,f)$ represents the out-of-plane velocity amplitude of the grid point with coordinates (x_i,y_i), $U_{ref}(f)$ is the excitation's voltage amplitude and $\sigma(f)_{(x,y)\notin\Omega}$ stands for the standard deviation of V_z of the points outside the damaged area at frequency f. When the damaged area shows a high SNR, it can be differentiated from the surrounding sound area by eye or by image processing software.

Next to the image of the operational deflection shape (ODS) (resulting from FFT), the frequency band data (FBD) is used to present the vibrometric response of the sample. The FBD of a scan point at location (x_i,y_i) is defined as:

$$\mathrm{FBD}(x_i, y_i, f_1, f_2) = \frac{f_{resolution}}{f_2 - f_1} \sum_{f=f_1}^{f_2} \frac{V_z(x_i, y_i, f)}{U_{Ref}(f)} \tag{2}$$

where $f_{resolution}$ is the frequency resolution of the FFT data and f_1, f_2 must lie within the frequency bandwidth of the excitation signal (see Table 1). Thus the FBD gives the vibrational amplitude averaged over a frequency band. Because a damaged area is typically characterized by a local reduction in bending stiffness, and as a result an increased out-of-plane vibrational amplitude (especially at LDR), it shows a higher FBD value compared to a sound area.

4. Results and Discussion

4.1. Flat Bottom Holes

For each of the three samples, the LDR frequencies are extracted out of the FFT dataset by manual peak-picking in the FRF and by analyzing the corresponding ODS. Figure 1a–c shows respectively the FBD over the entire excitation bandwidth, the ODS at LDR of the three FBHs with the lowest remaining material thickness and a picture of the coupon with FBHs of diameter 15 mm where the thickness of each FBH is specified. Figure 1d summarizes the SNR for all FBHs showing LDR behavior.

Logically, the f_{LDR} increases with increasing FBH thickness (and with decreasing FBH diameter). The SNR varies differently. Figure 1d indicates that the SNR is predominately influenced by the FBH thickness. As the FBH thickness increases, the local reduction in bending stiffness is decreased and so does the local amplitude of vibration under LDR. As a result, the SNR decreases up to the point that no LDR behavior could be identified. For all three coupons, this was the case for the 2 most shallow FBHs (>3.10 mm remaining material thickness).

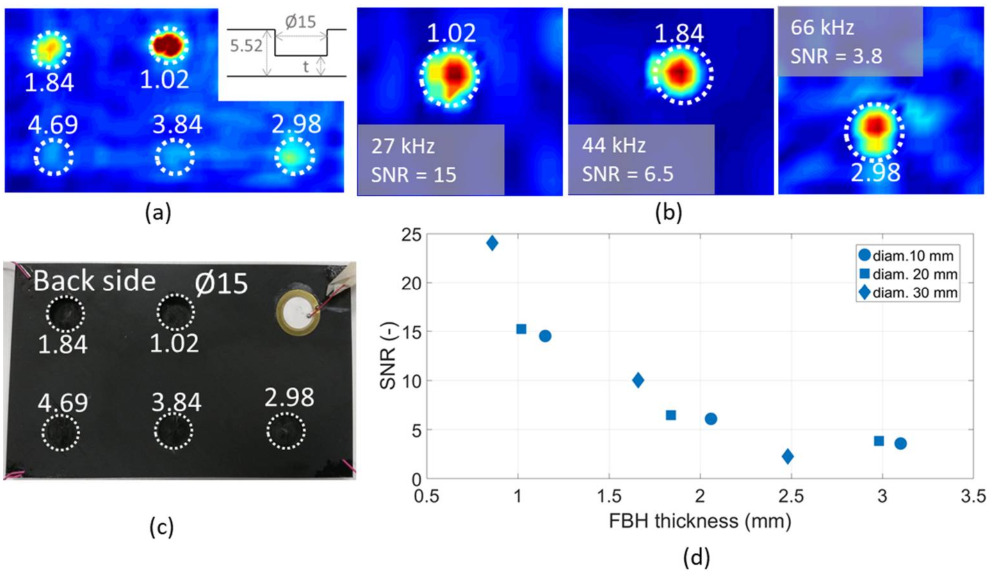

Figure 1. LDR for FBHs. (**a**) FBD over entire excitation bandwidth (**b**) ODS at LDR and (**c**) picture for the coupon with FBHs of diameter 15 mm; (**d**) SNR for all FBHs showing LDR behavior.

4.2. ETFE Inserts

Inserts are used to mimic delaminations in the investigation of numerous NDT techniques. Figure 2d shows the manufactured sample on which the location and depth of each insert are marked. After sample production, vibrometric and ultrasonic C-scan inspection in transmission mode are performed. Figure 2(a.1) shows the FBD of the total measurement bandwidth (f_1 = 5 kHz and f_2 = 80 kHz) calculated using Equation (2) while Figure 2(c.1) shows the corresponding ultrasonic C-scan. The FBD shows that there is an increased vibrational response at the locations of the inserts but not over the entire insert's area. The C-scan also indicates a difference in acoustic impedance between the 'active' and 'inactive' insert's areas. Therefore, the test sample has been manually impacted twice with gentle hammer strokes over the total area of the sample. Figure 2(a.2–a.3) and Figure 2(c.2–c.3) show the FBD and the C-scan of the sample after respectively the first and second impact cycle. The impacting procedure results in both an increased vibrational response and an increase in contrast of the C-scan. Figure 2(c.3) further indicates that no additional damaged was introduced by this procedure.

The measurements indicate that the high pressure, high temperature curing cycle of the CFRP material resulted in sticking of the insert's layers. Slightly impacting helps to separate the layers and thereby 'activate' the increased vibrational response and LDR behavior. This investigation shows that there is a clear difference between thin inserts and (artificial) delaminations when they are studied with vibrometry (e.g., LDR). It also indicates that artificial delaminations can be easily detected using the concept of FBD.

The same sample has also been inspected from the back side. The FBD presented in Figure 2b shows that the inserts deeper as mid-thickness (=1.3 mm) show much less contrast (remark the difference in the colorscale limits). This is attributed to the relative high material thickness at the defect. Similar observations were made in the previous section about FBHs.

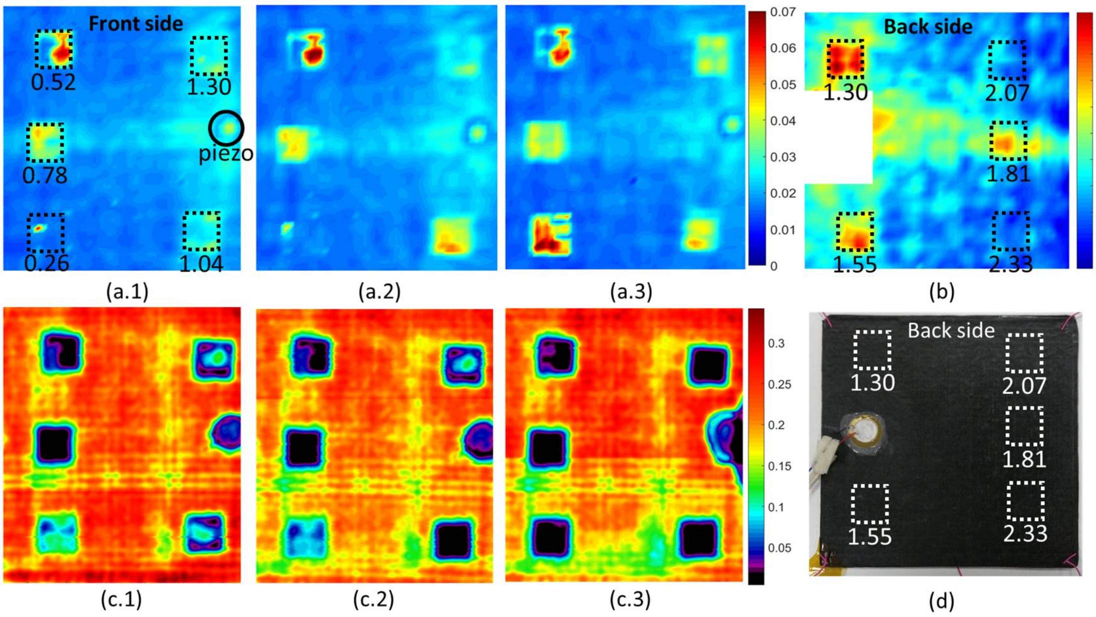

Figure 2. ETFE inserts: FBD over entire excitation bandwidth for (**a**) back side scan and (**b**) front side scan (remark the difference in the colorscale limits) and (**c**) ultrasonic C-scan before and after impact cycles; (**d**) Sample picture.

4.3. Barely Visible Impact Damage

BVID in a composite plate manifests itself typically as a complex pattern of delaminations and matrix cracks. The damage is distributed in the area near the impact zone and cannot be considered as a single idealized defect, which will obviously complicate the LDR analysis.

The test sample is inspected from the impact side (i.e., front) and back side. Over the large measurement bandwidth of 100 kHz, multiple small regions within the global damaged area show LDR behavior at different frequencies. The FBD is calculated (using Equation (2) with f_1 = 5 kHz and f_2 = 100 kHz) for defect evaluation as it summarizes the vibrational response over the large excitation bandwidth (see Figure 3b,c). Figure 3a shows an ultrasonic C-scan in reflection mode performed at 5 MHz as a reference. Using the FBD, the damaged area is visualized for both LDV scans. As such, the concept of LDR combined with FBD shows the ability to detect impact damage in CFRP without the need of excessive post-processing.

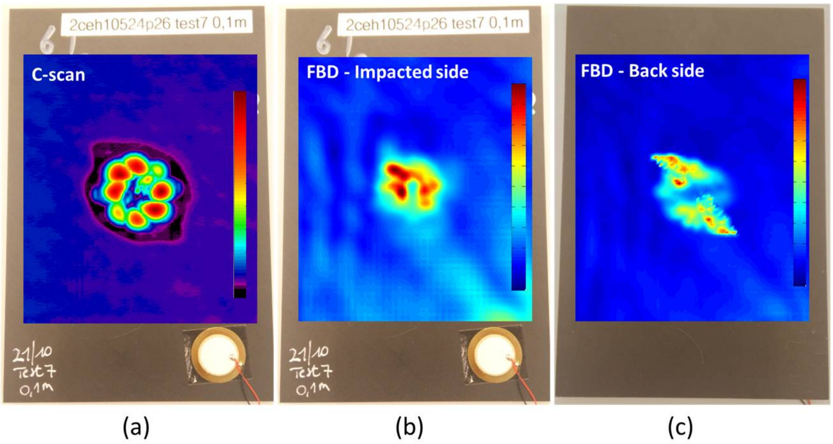

Figure 3. Picture with ultrasonic C-scan in reflection mode at 5 MHz (**a**) and frequency band data (FBD) over entire excitation bandwidth for broadband vibrometric inspection of a CFRP coupon with BVID from the impacted (**b**) and the back (**c**) side.

5. Conclusions

In this study, the concept of LDR is investigated for three different types of damages in CFRP coupons, namely: FBHs, inserts and BVID. For the evaluation of the LDR behavior for FBHs, a SNR ratio is introduced. The results indicate that the FBHs show LDR behavior only when they have a limited depth. Increasing the FBH remaining thickness results in a decreased SNR at LDR up to the point where no LDR could be manually identified. Similar results were found for the inserts with respect to their depth in the CFRP laminate. Here it was also shown that for vibrometric inspection, the inserts need to be detached from the epoxy matrix. This can be achieved by gently impacting the laminate. The detached inserts than mimic delaminations. At last, the concept of LDR combined with the calculation of the FBD showed promising results for assessing BVID in CFRP coupons.

Author Contributions: J.S., M.K. and W.V.P. conceived and designed the experiments; J.S. performed the experiments; J.S. and M.K. analyzed the data; S.H. and J.C. contributed analysis tools; E.V. contributed C-scan data; J.S. wrote the paper.

Acknowledgments: Joost Segers is a PhD fellow of the Research Foundation-Flanders (FWO, Grant no. 1148018N) and further acknowledges the SBO project DETECT-IV (Grant no. 160455), which fits in the SIM research program MacroModelMat (M3) funded by SIM (Strategic Initiative Materials in Flanders) and VLAIO (Flemish government agency Flanders Innovation & Entrepreneurship).

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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