Journal Pre-proof

Backside delamination detection in composites through local defect resonance induced nonlinear source behavior

Joost Segers, Saeid Hedayatrasa, Gaétan Poelman, Wim Van Paepegem, Mathias Kersemans

PII: S0022-460X(20)30191-7

DOI: https://doi.org/10.1016/j.jsv.2020.115360

Reference: YJSVI 115360

To appear in: *Journal of Sound and Vibration*

Received Date: 13 January 2020

Revised Date: 30 March 2020

Accepted Date: 30 March 2020

CRediT author statement

Joost Segers: Methodology, Software, Investigation, Writing, Visualization

Saeid Hedayatrasa: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing

Gaétan Poelman: Conceptualization, Writing - Review & Editing

Wim Van Paepegem: Conceptualization, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition

Mathias Kersemans: Conceptualization, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition

Backside delamination detection in composites through local defect resonance induced nonlinear source behaviour

Joost Segers[1#], Saeid Hedayatrasa[1,2], Gaétan Poelman[1], Wim Van Paepegem[1] and Mathias Kersemans[1]

[1] Mechanics of Materials and Structures (UGent-MMS), Department of Materials, Textiles and Chemical Engineering (MaTCh), Ghent University, Technologiepark-Zwijnaarde 46, 9052 Zwijnaarde, Belgium

[#] Corresponding author, Joost.Segers@ugent.be

[2] SIM Program M3 DETECT-IV, Technologiepark-Zwijnaarde 48, B-9052 Zwijnaarde, Belgium

Abstract

Shallow damages can be detected by searching for local defect resonance behavior in the fundamental vibrational response. However, this is not possible for defects which are deeper than half the thickness of the coupon due to the limited bending stiffness difference between the defect and the sound material.

In this study, it is shown that delaminations under harmonic excitation at the local defect resonance frequency behave as sources of higher harmonic vibration components. These higher harmonic components are detectable when examining the delaminated component from the side where the delamination is close to the surface, but more importantly, also from the other side where the delamination is at the backside. As such, monitoring of these harmonics allows for the detection of backside delaminations which cannot be found using linear LDR techniques. First, a finite element simulation with nonlinear contact conditions is performed as a proof of concept. Experimental validation is performed for a delaminated CFRP coupon using low-power piezoelectric actuation and scanning laser Doppler vibrometer response measurements.

Keywords

Composites, NDT, Nonlinearity, Local defect resonance, Higher harmonics, Laser Doppler vibrometry

1. Introduction

The non-destructive testing (NDT) method developed in this study builds on the concept of local defect resonance (LDR) [1, 2]. As the name indicates, an LDR is a localized amplification of the vibrational response (i.e. a resonance) at the defect. When the specimen is excited at an LDR frequency, the defect can be pinpointed, and to a certain extent evaluated, by measuring the structure's operational deflection shape (ODS). In general, a scanning laser Doppler vibrometer (SLDV) is used to measure the full-field vibrational surface response. As the existence of LDR is linked to the difference in stiffness between the defect and the surrounding sound material, it is clear that the detection of defects, which are located deep inside the coupon, with LDR is problematic. A recent study of the current authors indicated that the classical LDR can detect defects up to a depth of 50% (relative to full thickness of the sample) [3]. Enhanced defect detection is possible using nonlinear defect imaging, exploiting the relatively high vibrational activity of the defect under LDR frequency excitation [4-8]. The high vibrational activity at the defect results in a nonlinear response to vibrations caused by multiple mechanisms: contact, friction, viscoelastic damping, etc. [8-11]. Which of these mechanisms is dominant depends on the properties of the defect as well as the characteristics of the vibration field (e.g. dominant in—plane versus out-of-plane) [11, 12]. However, until now deep defect detection in monolithic composite components has not been demonstrated under LDR condition.

In this study, the nonlinear response of delamination in carbon fiber reinforce polymer components is further investigated. It is demonstrated that delaminations behave as sources of higher harmonics (HH) when the excitation frequency matches the LDR frequency. Moreover, it is numerically and experimentally proven that this nonlinear source behavior is visible from both sides of the component. This allows for the detection of shallow delaminations, and more importantly, it allows for the detection of deep, backside, delaminations.

2. Simulation: proof of concept

As a proof of concept, an explicit finite element simulation (ABAQUS) is performed for a 180x165x2 mm^3 CFRP coupon, with layup $[(0/90)_2]_s$, using 115736 linear hexahedral elements. Orthotropic material properties are used in accordance with the material properties of the experimentally investigated coupon (see Table 3 in Ref. [13]). A delamination defect of 20x20 mm^2 is modeled as a 2 µm gap between the first and second ply, and both normal (hard contact) and tangential (friction) interactions are prescribed. This defect model allows for contact acoustic nonlinearity at the gap closures when the defect is resonated. A harmonic force excitation of 50 kPa amplitude and duration 2 ms is applied at the lower left corner over an circular area (diameter 20 mm). The excitation frequency is set to 28 kHz which corresponds to an LDR frequency of the modelled delamination. The vibrational surface response of both sides of the sample is analyzed in the frequency domain. At the fundamental frequency of 28 kHz, the LDR behavior of the defect is clearly visible from the Shallow Side (see Figure 1(a)). From the Deep Side however, no indication of the defect is observed due to the limited stiffness mismatch between sound material and the thick side of the delamination (Figure 1(b). At the second and third higher harmonic frequencies (f_{HH2} = 2 x 28 kHz and f_{HH3} = 3 x 28 kHz respectively), the delamination shows a relatively high amplitude of vibration. While this high amplitude of vibration is especially visible from the Shallow Side (Figure 1(c,e)), it is clear that the HH components are also clearly visible from the Deep Side (Figure 1(d,f)).

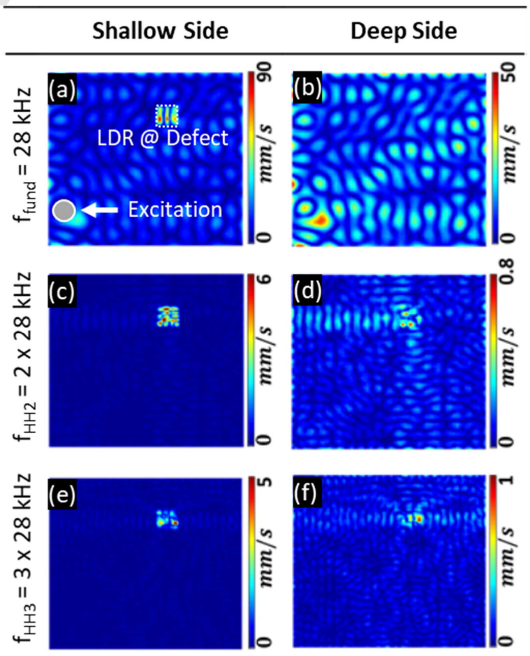

Figure 1: Operational deflection shapes at fundamental excitation frequency f_{fund} and at second and third higher harmonic frequency (f_{HH2}, f_{HH3}) for sine excitation at LDR frequency – Simulation results.

3. Experiment: validation

Furthermore, experimental verification is performed using an eight ply 290x140x2.2 mm^3 CFRP coupon with layup $[(0/90)_2]_s$ (see Figure 2(a)). Similar to the FE model, a 20x20 mm^2 delamination is present between the first and second ply. The delamination is made by inserting two layers of 25 µm thick brass foil between the plies. Vibrations are introduced using two low power piezoelectric actuators (EPZ-20MS64W Ekulit) bonded to the Deep Side surface using phenyl salicylate. In all experiments, both actuators are supplied with an identical signal. A Falco systems wma-300 voltage amplifier is used to increase the voltage supplied to the actuators. The surface of the coupon is covered with reflective tape (3M™Scotchlite™) to increase the signal-to-noise ratio of the acquired signals. The full-field surface vibrations are obtained using a 3D infrared SLDV (Polytec PSV-500-3D-Xtra). In this study, only the out-of-plane velocity component V_Z is used. The vibrations are measured from both the Shallow Side as well as the Deep Side.

As a first step, the LDR behavior of the delamination is investigated. To this end, the actuators are supplied with a 50 Vpp sweep signal from 1 to 100 kHz and the measured velocity response is analyzed for both sides of the coupon. At each frequency, the defect-to-background ratio *DBR* is calculated as:

$$DBR(f) = \frac{\Omega_{\text{healthy}}}{\Omega_{\text{defect}}} \frac{\sum_{i=1}^{n_{\text{defect}}} V_Z(x_i, y_{i,}, f)}{\sum_{i=1}^{n_{\text{healthy}}} V_Z(x_i, y_{i,}, f)} \quad (1)$$

Where Ω_{defect} is the defected area which contains n_{defect} measurement points and Ω_{healthy} is the surrounding healthy area with n_{healthy} measurement points. $V_Z(x_i, y_i, f)$ is the magnitude of out-of-plane velocity of the scan point at location (x_i, y_i) for the ODS corresponding to frequency *f*. As a result, a local maximum in the *DBR* curve is related to an LDR. The DBR curve, together with the average velocity amplitude at the location of the delamination (Vel_Z), is shown in Figure 2(b-c) for the Shallow and Deep Side of the delamination. From the Shallow Side, a clear LDR behavior is observed at 27 kHz as shown by the ODS (Figure 2(a)). However, from the Deep Side of the sample, no LDR behavior is present due to the limited stiffness mismatch between the sound material (8 plies) and the thick part of the delamination (7 plies). Thus, the exploration of the nonlinear defect response is necessary in order to detect the deep delamination.

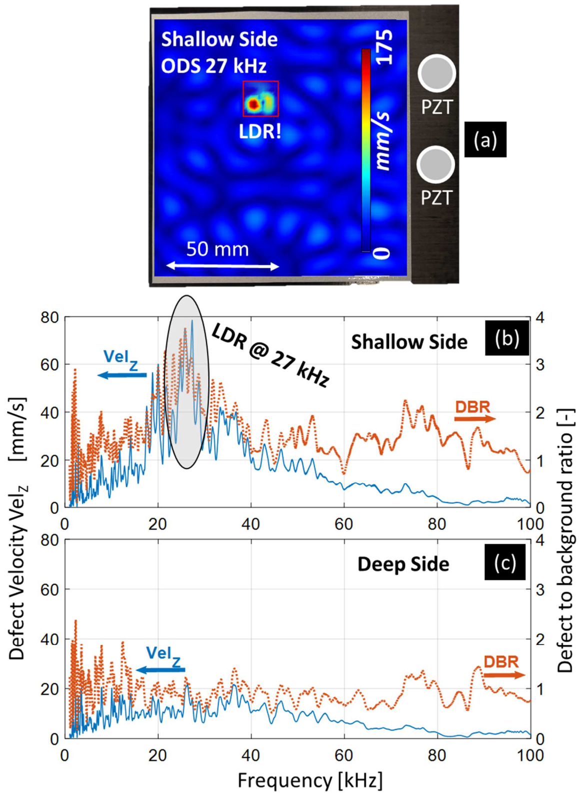

Figure 2: (a) Test specimen as seen from the side where the delamination is close to the surface (i.e. Shallow Side) with operational deflection shape at the LDR frequency of 27 kHz. Defect-to-background ratio *DBR* and defect velocity response Vel_Z at delamination as measured from (b) Shallow Side and (c) Deep Side.

In the next step, the sample is harmonically excited at the above identified LDR frequency of 27 kHz with a 150 V_{pp} signal. The resulting ODSs corresponding to the fundamental frequency (f_{fund} i.e. the excitation frequency) and the higher harmonics (HH_i with $f_{\text{HHi}} = i * f_{\text{fund}}$) are shown in Figure 3. The results are available in animated format in the online version of this article.

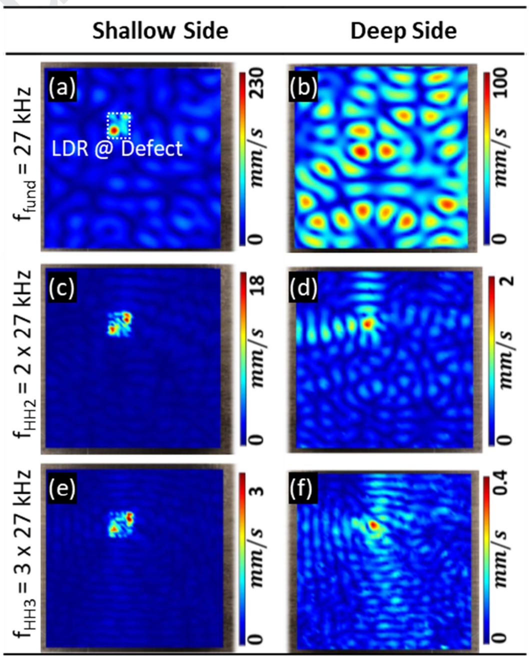

Figure 3: Operational deflection shapes at fundamental excitation frequency f_{fund} and at second and third higher harmonic frequency (f_{HH2}, f_{HH3}) for sine excitation at LDR frequency – Experimental observations.

This experimental observation is highly similar to the numerical observation (see Figure 1). The ODS at f_{fund} displays LDR behavior at the Shallow Side of the delamination, while there is no indication of the delamination from the Deep Side. The ODSs corresponding to the HH frequencies on the other hand show a local high amplitude at the defect and, more importantly, the defect behaves as a source, radiating these harmonics to the surrounding sound material (see also the animated figure). This source behavior is most pronounced at the Shallow Side but is also clearly visible from the Deep Side.

To further prove that the HH components are present due to the defect nonlinearity, and not as a result of potential source nonlinearity, the specimen is excited using a sine frequency at f = 54 kHz. The obtained fundamental ODSs (Figure 4(a,b)) are compared with the ODSs of the HH_2 component (sine excitation at f = 27 kHz) found earlier (Figure 4(c,d)). The large mismatch in ODSs indicates that the HH_2 vibrations are indeed dominantly excited by the defect and are not related to source nonlinearity.

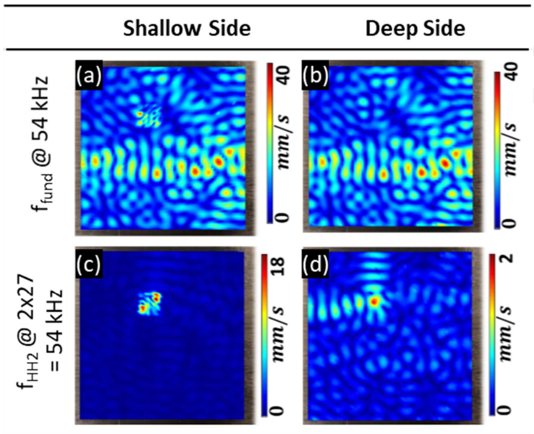

Figure 4: Operational deflection shapes at 54 kHz when excited using (a,b) 54 kHz sine, versus, (c,d) 27 kHz sine (see Fig 3(c,d)).

4. Conclusion

In this study, the nonlinear response of a vibrating delamination defect in a CFRP plate under harmonic excitation at the local defect resonance frequency is investigated experimentally as well as using numerical simulation.

It is shown that the defect under LDR behavior behaves as a radiating source of higher harmonic components, visible from both sides of the component. This observation is of great importance for the field of vibrometric non-destructive testing (NDT) as well as structural health monitoring (SHM). It evidences that backside delaminations can be detected and localized by evaluating the local amplitude of the HHs over the test specimen surface using SLDV measurements. Furthermore, the observed source nature of the induced defect nonlinearity allows the use of HH source localization algorithms in case of sparse array sensor networks.

Acknowledgments

The authors acknowledge Fonds voor Wetenschappelijk Onderzoek FWO (fellowships 1148018N, 1S11520N and 12T5418N) and the SBO project DETECT-IV (Grant no. 160455), which fits in the SIM research program MacroModelMat (M3) coordinated by Siemens (Siemens Digital Industries Software, Belgium) and funded by SIM (Strategic Initiative Materials in Flanders) and VLAIO (Flemish government agency Flanders Innovation & Entrepreneurship).

References

1. Tenek, L.H., E.G. Henneke, and M.D. Gunzburger, *Vibration of delaminated composite plates and some applications to non-destructive testing.* Composite Structures, 1993. **23**: p. 253-262.
2. Solodov, I., et al., *A local defect resonance to enhance acoustic wave-defect interaction in ultrasonic nondestructive evaluation.* Applied Physics Letters, 2011. **99**(21).
3. Segers, J., et al., *Probing the limits of full-field linear Local Defect Resonance identification for deep defect detection.* Ultrasonics, 2020.
4. Pieczonka, L., et al., *Damage imaging in composites using nonlinear vibro-acoustic wave modulations.* Structural Control and Health Monitoring, 2017.
5. Fierro, G.P.M. and M. Meo, *A combined linear and nonlinear ultrasound time-domain approach for impact damage detection in composite structures using a constructive nonlinear array technique.* Ultrasonics, 2018. **93**: p. 43-62.
6. Zhang, S., et al., *Far-sided defect recognition of FRP sandwich structures based on local defect resonance.* Journal of Sandwich Structures & Materials, 2019(April): p. 1-12.
7. Roy, S., T. Bose, and K. Debnath, *Detection of local defect resonance frequencies using bicoherence analysis.* Journal of Sound and Vibration, 2019. **443**: p. 703-716.
8. Solodov, I., *Resonant Acoustic Nonlinearity of Defects for Highly-Efficient Nonlinear NDE.* Journal of Nondestructive Evaluation, 2014. **33**(2): p. 252-262.
9. Ciampa, F., G. Scarselli, and M. Meo, *On the generation of nonlinear damage resonance intermodulation for elastic wave spectroscopy.* The Journal of the Acoustical Society of America, 2017. **141**(4): p. 2364.
10. Fierro, G.P.M., et al., *Nonlinear ultrasonic stimulated thermography for damage assessment in isotropic fatigued structures.* Journal of Sound and Vibration, 2017. **404**: p. 102-115.
11. Ooijevaar, T.H., et al., *Nonlinear dynamic behavior of an impact damaged composite skin–stiffener structure.* Journal of Sound and Vibration, 2015. **353**: p. 243-258.
12. Segers, J., et al., *In-plane local defect resonances for efficient vibrothermography of impacted carbon fiber-reinforced polymers (CFRP).* NDT & E International, 2019. **102**: p. 218-225.
13. Martens, A., et al., *Characterization of the orthotropic viscoelastic tensor of composites using the Ultrasonic Polar Scan.* Composite Structures, 2019. **230**.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: