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## Non-Destructive Evaluation of Kissing Bonds using Local Defect Resonance (LDR) Spectroscopy: A Simulation Study

S. Delrue<sup>a</sup>, M. Tabatabaeipour<sup>a</sup>, J. Hettler<sup>a</sup>, K. Van Den Abeele<sup>a</sup>

<sup>a</sup>Wave Propagation and Signal Processing, Department of Physics, KU Leuven - Kulak, 8500 Kortrijk, Belgium

### Abstract

With the growing demand from industry to optimize and further develop existing Non-Destructive Testing & Evaluation (NDT&E) techniques or new methods to detect and characterize incipient damage with high sensitivity and increased quality, ample efforts have been devoted to better understand the typical behavior of kissing bonds, such as delaminations and cracks. Recently, it has been shown experimentally that the nonlinear ultrasonic response of kissing bonds could be enhanced by using Local Defect Resonance (LDR) spectroscopy. LDR spectroscopy is an efficient NDT technique that takes advantage of the characteristic frequencies of the defect (defect resonances) in order to provide maximum acoustic wave-defect interaction. In fact, for nonlinear methodologies, the ultrasonic excitation of the sample should occur at either multiples or integer ratios of the characteristic defect resonance frequencies, in order to obtain the highest signal-to-noise response in the nonlinear LDR spectroscopy. In this paper, the potential of using LDR spectroscopy for the detection, localization and characterization of kissing bonds is illustrated using a 3D simulation code for elastic wave propagation in materials containing closed but dynamically active cracks or delaminations. Using the model, we are able to define an appropriate method, based on the Scaling Subtraction Method (SSM), to determine the local defect resonance frequencies of a delamination in a composite plate and to illustrate an increase in defect nonlinearity due to LDR. The simulation results will help us to obtain a better understanding of the concept of LDR and to assist in the further design and testing of LDR spectroscopy for the detection, localization and characterization of kissing bonds.

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### 1. Introduction

Kissing bonds, such as cracks or delaminations, are closed defects that can be consecutively opened and closed by applying a finite excitation amplitude that is able to overcome the defect's specific activation threshold. This local contact behavior (commonly referred to as kissing, breathing or clapping) gives rise to a nonlinear stress-strain relation at the defect location since the stress-strain response is different in tension than in compression (violation of the simple Hooke's law). This is evidenced by the frequency spectrum of the nonlinear structural response which

\* Corresponding author. Tel.: +3256246087.

E-mail address: [Steven.Delrue@kuleuven-kulak.be](mailto:Steven.Delrue@kuleuven-kulak.be)

is no longer dominated only by the frequency of the excitation signal. Higher order harmonics and subharmonics, whose frequencies have a prescribed relation with the excitation frequency, appear in the spectrum as a result of the nonlinearity [? ? ? ? ? ].

During the last few years, several studies have been performed to increase the efficiency of the nonlinear ultrasonic detection of incipient damage. By using for instance a resonant excitation of the sample under study, the nonlinear defect response (sub- or higher harmonic generation) can be enhanced [? ? ]. Another way to enhance the nonlinear acoustic response was recently suggested by the group of Prof. Solodov et al. and is called Local Defect Resonance (LDR) spectroscopy [? ? ? ]. LDR spectroscopy is a novel and efficient NDT technique that takes advantage of characteristic frequencies of the defect (defect resonances) in order to provide maximum acoustic wave-defect interaction. Using the concept of LDR, i.e. applying ultrasonic excitation frequencies tuned to the defect, it has been shown experimentally that the conditions for enhanced linear and nonlinear activity of the defects can be optimized.

In this paper, a numerical study is performed to illustrate the existence of LDR, to define an appropriate method to determine LDR frequencies and to illustrate how the defect nonlinearity is increased by exciting the sample under study at the LDR frequency. The simulation results discussed in this paper will help us to obtain a better understanding of the concept of LDR and to assist in the further design and testing of LDR spectroscopy.

## 2. LDR observation and spectroscopy

Resonance frequencies and corresponding vibration patterns in a sample can be determined by exciting the sample with a wide-band ultrasonic signal (e.g. linear sweep or chirp) in combination with a scan of the sample surface displacements. A Fourier transform of the displacement signals will then reveal the resonance frequencies. Kissing bond resonance frequencies, however, will mostly be missed by this method as the defect faces vibrate at much lower amplitudes when compared to the plate vibrations. Therefore, a novel method is proposed, in which Fourier transform spectroscopy is combined with the Scaling Subtraction Method (SSM) [? ]. In SSM, the response of a very low amplitude excitation is compared with that of a high amplitude excitation. At low excitation amplitudes, the kissing bond is not excited and therefore has no influence on the measured response. At high excitation amplitudes, however, the kissing bond activation threshold is overcome and the defect is successively opened or closed, influencing the measured surface displacements. Nonlinear defect features are extracted from the signals by using the low amplitude responses as a reference signal which, linearly rescaled in amplitude, is subtracted from the high amplitude responses.

We have applied the concept of SSM to our simulations to determine local defect resonance frequencies of a circular delamination in a unidirectional (anisotropic) carbon fiber composite with density  $\rho = 1800 \text{ kg/m}^3$ . The composite plate has a length and width of 50 mm, and a thickness of 2 mm, as illustrated in Fig. 1. The delamination, positioned parallel to the plate surface, has a diameter of 10 mm and is centered at  $x = 20 \text{ mm}$  and  $y = 30 \text{ mm}$ , at a depth of 0.4 mm with respect to the top surface of the plate. An external ultrasonic circular source with a diameter of 10 mm, located at  $x = 10 \text{ mm}$  and  $y = 10 \text{ mm}$ , is introduced in the model by applying an out-of-plane (normal) displacement boundary condition at the top surface of the sample. The 3D numerical model for wave propagation in the considered composite plate uses the commercially available finite element based software package COMSOL Multiphysics, in combination with our own custom-developed clapping model in order to simulate the macroscopic nonlinear clapping behavior of the delamination [? ]. The sample is first excited with a low amplitude ( $A_{low}$ ) linear sweep signal that extends from 10 kHz to 100 kHz in 2 ms. During this low amplitude excitation the normal displacements at the top surface of the sample are determined. Subsequently, the sample is excited using a high amplitude linear sweep signal ( $A_{high} = nA_{low}$ ). Again, normal displacements are determined at the top surface of the sample. If we then subtract the reference signal (i.e. low amplitude signal), multiplied by a factor  $n$ , from the normal displacements of the second simulation, the linear contribution is eliminated from the signal, and only the nonlinear contributions at the top surface of the sample remain.

In order to determine local defect resonances, we first temporally Fourier transform the scaling subtracted signals at each point on the sample surface. Subsequently we identify the maximum amplitude in the spatial 2D picture for each response frequency. The result of this procedure is plotted in Fig. 2(a) (top figure, full line). The peaks observed in the maximum amplitude response occur at frequencies at which the kissing bond is strongly excited, and therefore correspond to either sample resonance frequencies or local defect resonance frequencies. To distinguish between plate resonances and defect resonances, we repeated the same procedure on two bigger samples ( $60 \times 60 \times 2 \text{ mm}^3$

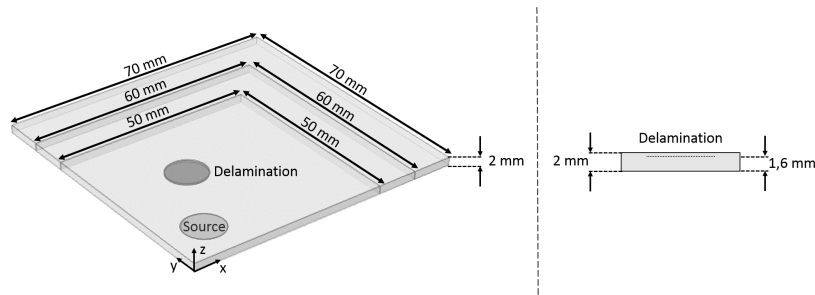


Fig. 1. Illustration of the three composite square plates used in the simulations. The plates contain a circular delamination with a diameter of 10 mm, centered at  $x = 20$  mm and  $y = 30$  mm, at a depth of 0.4 mm, with respect to the top surface of the plate. An ultrasonic circular source with a diameter of 10 mm is located at  $x = 10$  mm and  $y = 10$  mm.

and  $70 \times 70 \times 2$  mm<sup>3</sup>) containing the same delamination (see Fig. 1). The maximum amplitude responses for the new plates are also shown in Fig. 2(a) (top figure, dashed and dash-dot line). For the samples, we expect defect resonances to occur at the same frequencies. In order to highlight the possible defect resonance frequencies, we perform a point-wise multiplication of the three amplitude responses. The result of this multiplication is shown in the bottom figure of Fig. 2(a). LDR frequencies are finally obtained by retrieving the (scaling subtracted) mode shapes of the samples at the selected resonance frequencies. If the defect vibration patterns look similar for the three samples, a LDR mode is found. This is illustrated in Fig. 2(b), where the simulated mode shapes filtered around 64.4 kHz are plotted. In all three samples, the defect vibration pattern matches that of a higher order LDR mode.

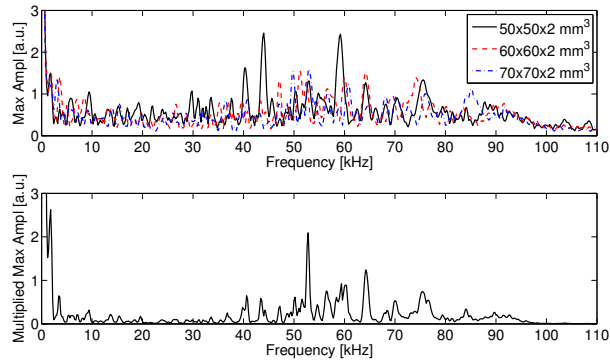
In LDR spectroscopy, the characteristic frequencies of the defect are used to provide maximum acoustic wave-defect interaction, resulting in a strong increase in defect nonlinearity. To illustrate this, we excited the first sample ( $50 \times 50 \times 2$  mm<sup>3</sup>) with continuous harmonic (mono-frequency) excitations at frequencies below and above the higher-order LDR frequency of 64.4 kHz. Fig. 3 shows the maximum higher harmonic amplitudes obtained over all positions located above the delamination on the top surface of the sample. When the excitation frequency matches the LDR frequency, an increase in higher harmonic amplitude is observed. The simulation results thus confirm that using LDR spectroscopy is indeed beneficial for the detection of kissing bonds.

### 3. Conclusion

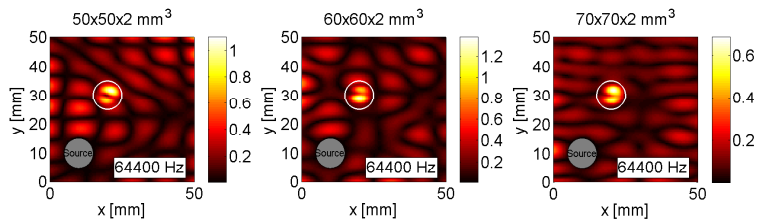
A simulation study was performed in order to illustrate the use of LDR spectroscopy for non-destructive evaluation of kissing bonds. An appropriate method, combining Fourier transform spectroscopy with the Scaling Subtraction Method (SSM), was proposed to determine local defect resonance frequencies of a circular delamination in a composite sample. We demonstrated that a strong increase in defect nonlinearity can be observed when the excitation frequency is tuned to the LDR frequency. In future, we will further exploit the model to obtain a better understanding of the concept of LDR and to assist in the optimization of LDR spectroscopy for applications in non-destructive testing.

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(a)



(b)

Fig. 2. (a) Top: Maximum amplitude response of the scaling subtracted signals at the top surface of the studied composite plates with delamination. Bottom: Point-wise multiplication of the maximum amplitude responses from the top figure. (b) Simulated vibration patterns filtered around 64.4 kHz for the three studied composite plates using the scaling subtracted signals. The white circle indicates the position of the circular delamination.

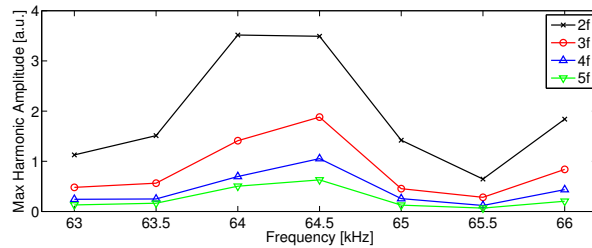


Fig. 3. Maximum higher harmonic amplitudes as function of excitation frequency.