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Detection of defect parameters using nonlinear air-coupled emission by ultrasonic guided waves at contact acoustic nonlinearities

Steven Delrue *, Koen Van Den Abeele

Wave Propagation and Signal Processing Research Group, KU Leuven Kulak, E. Sabbelaan 53, 8500 Kortrijk, Belgium

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ABSTRACT

Interaction of ultrasonic guided waves with kissing bonds (closed delaminations and incipient surface breaking cracks) gives rise to nonlinear features at the defect location. This causes higher harmonic frequency ultrasonic radiation into the ambient air, often referred to as Nonlinear Air-Coupled Emission (NACE), which may serve as a nonlinear tag to detect the defects. This paper summarizes the results of a numerical implementation and simulation study of NACE. The developed model combines a 3D time domain model for the nonlinear Lamb wave propagation in delaminated samples with a spectral solution for the nonlinear air-coupled emission. A parametric study is conducted to illustrate the potential of detecting defect location, size and shape by studying the NACE acoustic radiation patterns in different orientation planes. The simulation results prove that there is a good determination potential for the defect parameters, especially when the radiated frequency matches one of the resonance frequencies of the delaminated layer, leading to a Local Defect Resonance (LDR).

1. Introduction

Among many other techniques, ultrasonic guided wave techniques (GWT) have emerged as a prominent option for non-destructive testing of materials. The main advantage of GWT is the ability to scan large samples from a single source location, as guided waves can travel long distances with little loss in energy [1]. This results in substantial time and cost savings, particularly when compared to conventional point-by-point NDT methods which imply a slow and expensive process when full inspection coverage is needed. For this and other reasons, GWT nowadays have been widely used to inspect and monitor the structural health of a variety of engineering structures, e.g. pipelines, aircraft wing and fuselage panels, wind turbine blades, etc. [2–11]. The techniques are commonly based on reflection, diffraction and scattering of guided waves while interacting with defects, as well as on the occurrence of mode conversion. Proper analysis of various characteristics of the received signal, such as time of flight, amplitude and/or phase variations, etc., provides essential information about the presence of damage in the inspected sample [12–18].

The efficiency of the interaction of guided waves with defects depends on the size of the defect, as well as on the degree of degradation of the linear material properties caused by the damage. For incipient damage in the form of microcracks or delaminations, conventional GWT may fail to detect the defects due to a lack of acoustic impedance contrast. In such cases, other concepts of guided wave propagation can be proposed. In recent years, it was experimentally and numerically shown that for intense excitation, e.g. high amplitude Lamb wave excitation, the defect fragments of delaminations and cracks start to exhibit a non-classical clapping behavior, causing an efficient local generation of nonlinear frequency components, i.e. harmonics, subharmonics and modulated frequencies [19–22]. The generated nonlinear vibrations can be used as a nonlinear tag for defect detection since they cause high-frequency ultrasonic radiation into the ambient air, referred to as nonlinear air-coupled emission (NACE) [23,24].

This paper summarizes the results of a numerical implementation and simulation study of NACE using the commercially available software package COMSOL Multiphysics [25]. The developed finite element model combines a 3D time domain model for nonlinear Lamb wave propagation in delaminated samples [22] with a spectral solution for the nonlinear air-coupled emission. The model results confirm the NACE radiation patterns observed in experiments and illustrates the potential of detecting different defect parameters, such as shape, position and depth of the delamination by studying the NACE acoustic radiation patterns in different orientation planes.

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* Corresponding author. Tel.: +32 56246087.
E-mail addresses: Steven.Delrue@kuleuven-kulak.be (S. Delrue), Koen.VanDenAbeele@kuleuven-kulak.be (K. Van Den Abeele).

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2. Numerical modeling of NACE

A two-step 3D numerical model was implemented in the finite element based commercially available software package COMSOL Multiphysics. The first step of the model contains a 3D time domain model for the calculation of nonlinear Lamb wave propagation in delaminated samples. In the second step, radiation patterns in the ambient air are calculated by bridging the results of the time domain solution to a spectral solution of air. In this section, we briefly discuss the implementation of both steps in the model.

2.1. Nonlinear Lamb wave propagation

The model used to simulate the nonlinear clapping behavior at a delamination in a composite sample considers the introduction of a non-perfect bond between surfaces. This can be described by a set of virtual spring and damper forces at both sides of the delamination surface, as described in Ref. [22]. Above a certain separation threshold, the two sides are completely separated (stress-free surfaces). Below the threshold, particular formulations of the Vanderwaals forces are implemented. When the surfaces are close to each other, they will be attracted to each other. However, when they tend to be too close, the force will turn into a repulsive force, trying to separate the surfaces again. Apart from the elastic contact force, damping forces were also implemented as forces that are acting against the velocity of the separation. These forces make sure that the surfaces are not separating too abruptly, avoiding a destruction of the material. At the same time the damping forces assume that the two surfaces are not closing too fast either, so that they cannot overlap.

The nonlinear viscoelastic behavior at the delamination level, as described above, mimics the clapping behavior of the delamination. Depending on the displacement amplitude of a Lamb wave passing by the defect, its local nonlinearity will be activated or not, creating a distortion in the wave propagation, which can be measured after appropriate signal processing. Amplitudes must reach a certain threshold for the clapping nonlinearity to be activated. If the wave amplitudes are too low to separate the surfaces in case of a closed defect, there will be no influence in terms of spectral broadening on the wave propagation.

The implementation of the nonlinear spring and damper forces is performed by introducing dynamic boundary conditions in COMSOL at those nodes that correspond to the delamination surface. At these positions, the nodes were split in pairs and analytic formulas for the spring and damper forces were defined at each side of the pair. Typical parameters of kissing bond flaws, as for example the stiffness of the defect, can be adapted by changing various parameters in the model (introduced at the level of the delamination). A more detailed description of the nonlinear equation of state and its specific parameters can be found in Ref. [22].

2.2. Nonlinear air-coupled emission

The nonlinear air-coupled emission is modeled by using a simple 3D model in which radiation patterns are calculated at specific frequencies. A 3D rectangular air domain is modeled, in which all boundaries, except one (the bottom boundary), are defined as matched boundaries in order to eliminate unwanted reflections coming from the edges of the computational region. At the bottom boundary, a normal acceleration is defined as a 2D input source. The resulting radiation patterns can be calculated and studied in different orientation planes.

2.3. Combined model

In the present paper, a combination of the above described models is used to calculate nonlinear NACE patterns generated by the presence of a delamination in a composite sample. The modeled composite is a rectangular plate made of T300/924C, a carbon-fiber reinforced polymer, of which the effective material properties are given in Table 1. The plate dimensions are $400 \times 40 \times 5$ mm^3, as illustrated in Fig. 1. The sample contains a horizontal, ellipsoidal delamination with major axis length of 20 mm in the x-direction and minor axis length of 10 mm in y-direction (pink boundaries in Fig. 1). The delamination is positioned at a depth of 1 or 2 mm below the top surface (depending on the case studied). The plate is excited on the leftmost boundary (i.e. small x-values). The rightmost boundary is implemented as a low-reflecting boundary in order to prevent unwanted reflections from the edges of the computational region. For the front and back wall a periodic boundary condition is used. This periodicity imposes the displacement components from the front wall to be equal to those of the back wall. On top of the composite sample, a rectangular domain of air (blue domain in Fig. 1) is introduced, containing three different orientation planes for which the acoustic radiation patterns will be mapped.

The combined model is now solved as follows. First, the 3D time domain model, which only contains the delaminated composite plate and no ambient air, is considered. A high amplitude A_0 Lamb wave, either at 25, 50 or 100 kHz, is generated at the leftmost boundary of the sample. This is done using a mono-frequency sinusoidal displacement across the entire left boundary of the plate, corresponding to the theoretically calculated Lamb displacement profiles in x- and z-direction (the y-direction being obsolete at these frequencies). The generated Lamb wave propagates through the sample, and, once it reaches the ellipsoidal delamination, it disturbs the defect surfaces, initiating a clapping behavior, provided its amplitude is large enough to overcome the activation threshold. When activated, the clapping behavior causes the generation of harmonic and subharmonic components of the excitation frequency, which will be radiated in the surrounding air. In order to determine the NACE radiation patterns resulting from the generated nonlinear vibrations, the normal displacements at the top surface of the composite sample are determined. These displacements are then temporally Fourier transformed and filtered around a fixed response frequency, i.e. at the fundamental frequency or at some of its harmonics and subharmonics. The filtered responses are finally used as a boundary condition for the second model, using the 3D spectral solution of air above the test sample. This allows to determine radiation patterns at specific frequencies. In the post-processing analysis of the wave propagation model, the acoustic radiation is visualized using a set of orthogonal planes above the plate, as illustrated in Fig. 1. The xz-plane is positioned at $y = 20$ mm, the yz-plane is positioned at $x = 100$ mm and the xy-plane is positioned at $z = 5$ mm above the plate surface.

3. Defect characterization using NACE

As mentioned before, harmonics and subharmonics are generated by the clapping behavior of delaminations. Part of the wave

Table 1
Material properties of T300/924C.

Young's modulus [GPa]	Shear modulus [GPa]	Poisson's ratios
$E_{xx} = 127.1$	$G_{xy} = 5$	$\nu_{xy} = 0.32$
$E_{yy} = 8.34$	$G_{yz} = 2.7$	$\nu_{yz} = 0.461$
$E_{zz} = 8.85$	$G_{zx} = 4.8$	$\nu_{zx} = 0.009$