Simulation of Nonlinear Air-Coupled Emission from Defects

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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 indicator to detect the defects. In order to support the observations of NACE, a study has been performed using a numerical implementation and simulation 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 transmission into the ambient air. 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 quite good determination potential of the defect parameters, especially when the frequency of the radiated harmonic or subharmonic matches a resonance frequency of the delaminated layer.

Keywords: Modelling and Simulation, guided waves (Lamb waves), Ultrasonic Testing (UT), nonlinear, air-coupled, delamination, harmonic

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. GWT 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 \([2-8]\).

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 behaviour, causing an efficient local generation of nonlinear frequency components, i.e. harmonics, subharmonics and modulated frequencies \([9-12]\). 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) \([13,14]\).
This paper summarizes the results of a numerical implementation and simulation study of NACE using the commercially available software package COMSOL Multiphysics. The developed finite element model combines a 3D time domain model for nonlinear Lamb wave propagation in delaminated samples [12] with a spectral solution for the nonlinear transmission into the ambient air. The model results confirm the NACE radiation patterns observed in experiments and illustrate 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.

2. Numerical modelling of NACE

A numerical model for NACE simulations was developed using a 3D time domain model for the nonlinear Lamb wave propagation in a delaminated solid sample, in combination with a spectral solution for the radiated waves in the ambient air. The developed model consists of two steps. First, the time domain model is solved for the solid sample using an amplitude which is high enough to activate the defect fragments. The induced clapping at the defect interface, modelled by splitted nodes with dynamically changing nonlinear visco-elastic forces [12], results in spectral broadening on the wave propagation. The normal displacements caused by the distorted propagating wave are then used as a 2D input source to the spectral method to calculate the radiation into the ambient air.

The combined model geometry considered in the present study consists of a 5 mm thick plate made of a carbon fibre reinforced polymer with a 3D air domain on top, as illustrated in Figure 1. The composite 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 the y-direction (pink boundaries in Figure 1). The delamination is positioned at a depth of 2 mm below the top surface of the sample. The plate is excited on the leftmost boundary (i.e. small x-values) by a high amplitude \( A_0 \) Lamb wave, either at 25 or 50 kHz. 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. The generated Lamb wave propagates through the sample, and, once it reaches the defect, it disturbs the defect surfaces, initiating clapping behaviour, provided its amplitude is large enough to overcome the activation threshold of the delamination. When activated, the clapping behaviour will cause generation of harmonics, subharmonics or ultraharmonics, which will be radiated into the surrounding air. The resulting radiation patterns are analysed using a set of orthogonal planes above the plate, as illustrated in Figure 1.

3. Defect detection and characterization by NACE

3.1 Defect detection

For defect detection, only global information about harmonic and subharmonic generation in the sample is required. Therefore, for each response frequency, we identify the maximum amplitude in the spatial 2D picture of the top surface of the sample. Maxima are thus not linked to a specific location on the sample, but to the global maximum surface response at that frequency. In Figure 2, this maximum amplitude response is plotted for the modelled cases. Harmonics can be observed in both cases, however, it seems that they are more efficiently generated at lower excitation frequencies. Also at the lowest frequency of 25 kHz, ultraharmonic spectral components \((2f_{exc}/3, 5f_{exc}/3\) and \(7f_{exc}/3\)) are observed.
Figure 1. Model geometry consisting of a 5 mm thick plate made of a carbon fibre reinforced polymer (grey domain) and a 3D domain of ambient air (blue domain). The composite plate has a horizontal, ellipsoidal delamination with major axis length of 20 mm in $x$-direction and minor axis length of 10 mm in $y$-direction. The delamination is positioned at 2 mm below the top surface. In the air domain, three orientation planes are introduced for which the acoustic radiation patterns will be mapped. The $xz$ and $yz$ orientation planes contain the major and minor axis of the ellipsoidal delamination. The $xy$ orientation plane is positioned at a height of 5 mm above the plate surface.

Figure 2. Normalized maximum amplitude responses for a carbon fibre reinforced polymer plate with ellipsoidal delamination located at a depth of 2 mm below the sample surface. Results are shown for two different excitation frequencies: $f_{exc} = 25$ kHz and 50 kHz.
3.2 Defect characterization

Figures 3 and 4 show the typical output of the acoustic radiation at the excitation frequency (i.e. respectively 25 and 50) and its second and third harmonic. For the \(xz\) and \(yz\) orientation planes, we display the instantaneous acoustic pressure in air, which is a representation of the wavefront emission. The black lines indicate the cross-sectional dimensions of the defect (in this case, the ellipse). For the \(xy\) orientation plane, the method of displaying the acoustic radiation is incomplete, as instantaneous pressures do not necessarily capture the maximum pressure. Therefore, we plot the maximum pressure values. The colour scales at a certain frequency are normalized according to the maximum value for that frequency. The contours for different frequencies are therefore not represented on the same scale.

The illustrations show that it is immediately possible to discern the defect from the second and third harmonic radiation (\(2f\) or \(3f\)), however, not from the fundamental. The fundamental frequency fields display a regular radiation pattern created by the leaky Lamb wave propagating through the sample. For the harmonic radiation fields, the results in the \(xz\) and \(yz\) orientation planes show radiation that is originating within and mostly occurring above the defect position (i.e. in between the black lines). Such patterns can thus be used to get an idea of the extent of the defect in both \(x\) and \(y\) direction. As for the \(xy\) radiation plane, the nonlinear radiation results in high amplitudes at positions above the defect. Since high amplitudes are only found within or near the ellipse, this pattern can also be used to determine the dimensions of the defect. In addition, it may as well provide an indication of the shape of the defect. This is for instance the case in the third harmonic radiation field at 25 kHz (Figure 3), where a local defect resonance is observed. In most of the results, however, a certain asymmetry in the radiation pattern can be noted (e.g. \(xy\) and \(xz\) orientation planes at the second harmonic of 25 and 50 kHz). Possible explanations for this asymmetry can be linked to the angle of propagation of the Lamb wave and/or to the anisotropic behaviour of the material under study. However, further research is required to verify these suppositions.
Figure 4. Output dataset for harmonic frequencies generated by a horizontal ellipsoidal delamination positioned 2 mm below the sample surface and excited at $f = 50$ kHz.

Figure 5. Output dataset for three ultraharmonic frequencies generated by a horizontal ellipsoidal delamination positioned 2 mm below the sample surface and excited at $f = 25$ kHz.

Figure 5 shows a similar set of contours at selected ultraharmonic frequencies ($2f/3$, $5f/3$ and $7f/3$) for the studied sample, excited at $f = 25$ kHz. The radiation patterns illustrated in Figure 5 show that not all ultraharmonics provide unambiguous information. The higher the ultraharmonic frequency the better the location and shape of the defect can be determined. The frequency at which defects become visible depends on the dimensions of the defect, as they should match a resonance frequency of the defect. This is obviously the case at frequencies $5f/3$ and $7f/3$, where we clearly observe local defect resonances showing a different modal structure.
4. Conclusions

A numerical model for NACE simulations was developed using a 3D time domain model for the nonlinear Lamb wave propagation in a delaminated carbon fibre reinforced polymer sample, in combination with a spectral solution for the radiated waves in the ambient air. The developed model consists of two steps. First, the time domain model is solved for the solid sample using an amplitude which is high enough to activate the defect fragments. The induced clapping at the defect interface, modelled by splitted nodes with dynamically changing nonlinear visco-elastic forces, results in the generation of harmonic, subharmonic or ultraharmonic frequencies. The normal displacements at the solid-air interface are then used as input to the spectral method to calculate the radiation into the ambient air.

Using the combined numerical model, we studied the radiation patterns in three different orientation planes. The simulations confirmed that the concept of detecting delaminations using nonlinear air-coupled emission (NACE) is achievable in practice. Defects can be detected and characterised by studying the radiation patterns of (higher order) subharmonic frequencies and harmonic frequencies of the excitation frequency.

Further work is still required to establish the link between the used excitation frequency, the eigenmodes of the delaminated layer and the generated harmonic and subharmonic frequencies. Likewise, additional research is needed to explain the asymmetry observed in some of the output datasets. This could be investigated by making some small adaptations to the model (e.g. material properties, type of excitation, used Lamb mode, defect position, etc.). Once this is clear, we will also be able to study the effect of different orientations of a defect on the radiation patterns. We expect subharmonic frequencies to become important in this study as their presence is depth dependent.

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References