A numerical study on the applicability of nonlinear acoustics methods for damage imaging in composite laminates

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ABSTRACT

Recently there has been an increasing interest in the application of nonlinear acoustic methods for the detection of defects in various types of structures. Nonlinear acoustic methods typically involve providing an excitation signal to the structure and looking out for the nonlinear response. While the vibrations are linear in intact regions, nonlinear vibrations occur near the defect regions, which can be picked up for the identification of the damage in the structure. Most works till now have focused on nonlinear acoustic methods as a pass/fail test of defect detection and there have been only a few studies to evaluate the method for its damage imaging capabilities. To use nonlinear acoustic methods for damage imaging purposes, the vibration data need to be recorded at many points so that a continuous damage field could be obtained. For example, in case of a plate the data needs to be recorded along the surface at maximum number of locations. Since the experiments involve high frequencies and low amplitudes of vibrations the experimental setup typically requires scanning laser vibrometers for this purpose. However, before performing the experiments for the usage of nonlinear acoustic methods for damage imaging it is a good idea to conduct numerical simulations to verify the procedure in a virtual setup. It is to be noted that more challenges might arise in experiments later even after the technique is verified through a numerical framework and would require to be dealt accordingly.

The purpose of the current work is to present a numerical study to analyze the applicability of nonlinear acoustics as a damage imaging method for composite laminates in which internal defects in the form of delamination are commonly found. The developed model using commercial finite element package Abaqus/Standard has been taken from earlier literature and has been extended (parametrized) here to study the effect of several delamination scenarios. This extended numerical model will provide the flexibility to study the different damage scenarios which can be successfully scanned by nonlinear acoustic methods. Also, it can be used to predict the shortcomings of the technique where the method may fail to identify the damage map. In this parametric model, one set of parameters would correspond to one scenario of the imaging method. Several cases will be studied with this model which includes the effect of delamination size, its depth within the laminate, and its relative position with respect to the excitation signal. The cases of multiple delaminations within the composite laminate plate will also be studied. Different type of excitation signals typically used in nonlinear acoustics and their effect on the imaging prospects will be analyzed. Based on the results of the simulation cases strategies can be developed which could enhance the prospects of using the nonlinear acoustic methods as a damage mapping technique.

1. INTRODUCTION

The usage of composite materials has been increasing steadily over the years in the construction of aerospace structures due to their light weight, higher resistance to fatigue and corrosion in comparison to metals. But, due to their layer by layer configuration composite structures are more prone to internal damage than metals in which the damage mostly originates from the outside surface. The internal damage is usually in the form of delamination which occurs when the layers of the structure separate from each other due to the damage. Also, due to the brittle nature of composite materials there exists risk for sudden catastrophic failure. Due to this concern, there has been an increasing concern for internal damage monitoring in composite materials.

The linear ultrasonic methods based on the principles of transmission, reflection, and absorption of sound waves can help to monitor the delamination damage inside the composite structures. One form of the linear methods is the guided wave methods based on the propagation of lamb waves through thin structures and this method has shown significant potential to identify delaminations in composite structures [1]. However, there are certain types of defects which are not easy to be detected through linear ultrasonic methods. This includes defects in materials with low sound transmission, developing delaminations, and kissing bond defects. To diagnose this type of defects nonlinear methods have proven to be successful in many cases. Nonlinear methods are similar to linear methods and involve exciting the structure with waves and looking out for the response of the structure. The regions with defect vibrate in a nonlinear fashion and this nonlinearity need to be picked up by the nonlinear methods in order to successfully detect a defect. In composite materials, the nonlinearity may be caused by the opening and closing of the delamination gap, friction between the open delamination surfaces or fiber and matrix damage. A recent review of various nonlinear phenomenon and their impact on the damage detection process can be found in [2, 3].

There are also challenges associated with employing nonlinear methods to successfully detect damage. This includes separation of nonlinearity caused by damage and the nonlinearity due to other causes like boundary conditions, noise, instrumentation etc. to name a few. There are also challenges with mapping out the area of damage with nonlinear methods. The nonlinear methods should be highly sensitive and need to pick up the slightest of the nonlinear behaviour caused by the damage. Several experimental works have shown the potential of nonlinear methods to successfully diagnose the damage but these works are more focused on using it as pass/fail NDT test rather than as an imaging based method. Only recently these has been renewed interest in using nonlinear methods to map out the area of damage or delaminations. In order to map out the damage area there is a need to monitor the vibrations of as many points on the surface of the structure as possible. Previous works have shown that this can be achieved by using a laser scanning vibrometers (LSV) [4] or a grid of piezoelectric sensors. LSVs are expensive pieces of equipment while the piezoelectric sensors need to be physically attached to the structure leading to increased weight and inefficiency issues. This is one area of research where the damage diagnosis is done with the minimum number of sensors on the structure.

To optimise the damage detection process using nonlinear methods numerical simulations can play an important role and help us optimize the experimental setup in a virtual environment before setting up an actual experimental setup. To achieve this goal a previously developed numerical model [5] which simulates the nonlinear behaviour of a closed delamination in a composite plate upon exciting with a sinusoidal signal has been utilized. In this study, this numerical model has been extended to study various scenarios in which the nonlinear methods could successfully map out the damage area in a composite structure, a plate in this case. The details of the model and the various scenarios it could model are described in the next section.

2. MODEL DESCRIPTION

The nonlinear vibrations could occur due to various mechanisms including contact acoustic nonlinearity, friction, material nonlinearity etc. For numerical modelling the type of nonlinearity need to be known before hand in order to implement it in the model. In this work, the nonlinearity has been considered in the form of contact acoustic nonlinearity which occurs due to the opening and closing of the delaminations upon enduring the tension and compression cycles of the excitation signal. A three-dimensional (3D) model with geometry (shown here in Figure 1) based on the above contact acoustic nonlinearity condition has also been described in previous works [5, 6, 7]. The present study utilizes the model developed in [1] and extends it to determine the application of nonlinear methods on a wide case of scenarios.

2.1 Geometry and mesh

The geometry of the model has been shown in Figure 1. It consists of a square plate of 40 mm side length and 2 mm thickness. There exists a circular delamination of diameter 10 mm at a depth of 0.3 mm from the top surface shown in the cross-sectional view in Figure 1. It is to be noted that in later section different parameters related to the delamination namely its diameter, depth, position will be varied and its effect on the applicability of the method will be discussed. Scenarios with two delaminations will also be simulated. Figure 1 shows a model to be used as base case with delamination of diameter 10 mm situated at a depth of 0.3 mm in the center of the plate.

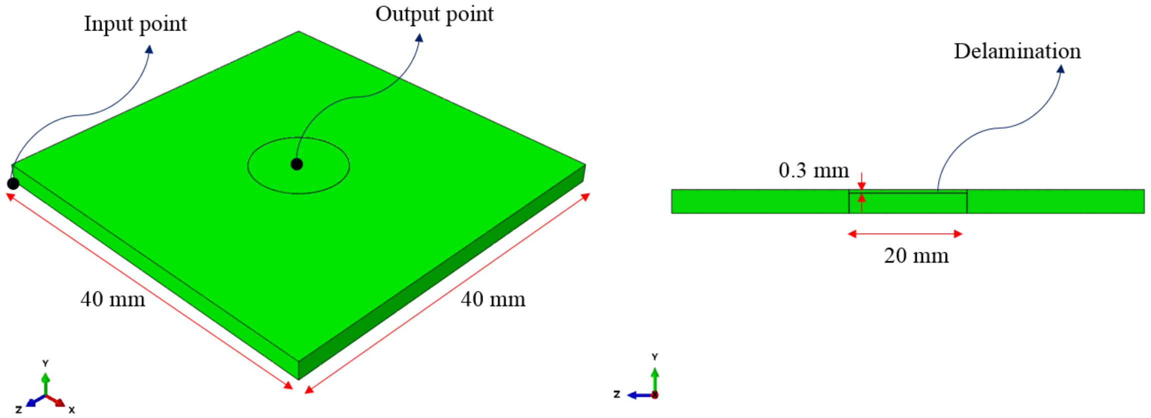

Figure 1: Geometry of the model. *Left:* Isometric view; *Right:* Cross-sectional view

The mesh used for the model is shown in Figure 2. A combination of tetrahedral and wedge elements with quadratic shape functions have been used. The mesh has also been refined on the top part of the delamination to accurately model the contact conditions between the delamination surfaces. Also, the mesh resolution has been kept in accordance with the mesh resolution requirement for wave propagation problems which requires a minimum of six elements per wavelength for accurate modelling.

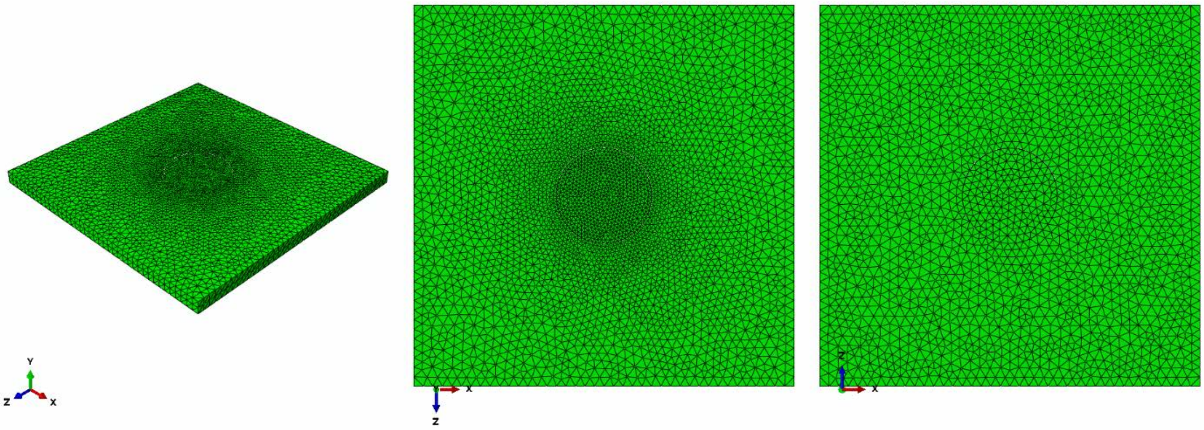

Figure 2: Mesh used for the model. *Left:* Isometric view; *Middle:* Top view; *Right:* Bottom view.

The plate is made up of a unidirectional carbon fiber reinforced composite material, the properties of which are listed in Table 1.

Property	Unit	Values
E_1	[GPa]	161.0
$E_2 = E_3$	[GPa]	11.38
$\nu_{12} = \nu_{13}$	–	0.32
ν_{23}	–	0.436
$G_{12} = G_{13}$	[GPa]	5.17
G_{23}	[GPa]	3.98
ρ	kg/m^3	1800

Table 1: Material properties of the plate

2.2 Excitation signals

Three generally used excitation signals are used at the input point (Figure 1). The details of these signals are described below:

2.2.1 Single frequency excitation (SFE)

The SFE signal is the basic sinusoidal excitation described by Equation 1.

$$x = A\sin(2\pi f) \tag{1}$$

where A is the amplitude of the signal and f is the excitation frequency. In these simulations, the amplitude (A) is taken as 1 µm and the excitation frequency is 25 kHz.

2.2.2 Vibro-acoustic modulation (VAM)

The VAM signal consists of a linear sum of two sinusoidal signals. The lower frequency is known as the pump frequency and the higher frequency is known as the probe frequency.

$$x = A_1\sin(2\pi f_1) + A_2\sin(2\pi f_2) \tag{2}$$

where A_1 and A_2 are the amplitudes of pump frequency (f_1) and probe frequency (f_2) respectively. In these simulations, the pump frequency is chosen as 5 kHz and its amplitude is 1 µm. The probe frequency is 100 kHz and its amplitude is 0.1 µm.

2.2.3 Sweep signal excitation (SWP)

The SWP signal also known as the chirp signal comprises of a signal in which frequency varies with time. A typical mathematical description of a linear chirp signal is described by Equation 3.

$$x = A\sin\left[2\pi\left(f_0 t + \frac{f_1 - f_0}{2T}t^2\right)\right] \tag{3}$$

where f_0 is the start frequency f_1 is the end frequency and T is the time it takes to sweep from frequency f_0 to frequency f_1. The simulations use 20 kHz as the start frequency and 30 kHz as the end frequency. The sweep time of the signal is 6.4 ms (128 cycles of the start frequency) and its amplitude is 1 µm.

The signals described above have been plotted for visual convenience in Figure 3 for both time domain as well as frequency domain.

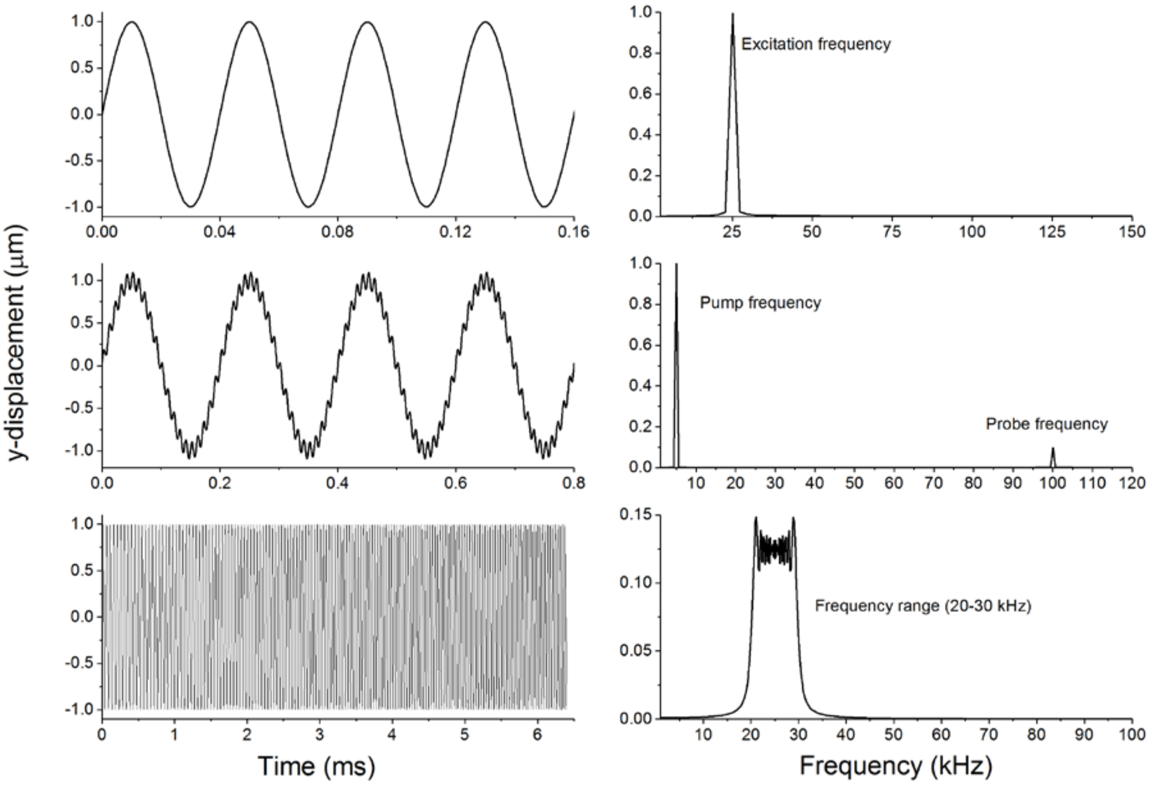

Figure 3: Input signal in time domain (left) and frequency domain (right). *Top:* SFE; *Middle:* VAM; *Bottom:* SWP

3. RESULTS

This section discusses the results of the simulation.

3.1 Excitation signal and the nonlinearity

The y-displacement time history of the output point (Figure 1) has been plotted in Figure 4 for all the three signals; SFE, VAM, and SWP.

For the SFE case the nonlinearity can be seen by the visible distortion of the y-displacement signal in time domain. In frequency domain, the nonlinearity is visible through the appearance of nonlinear frequencies in the form of higher harmonics (50 kHz, 100 kHz, 125 kHz) of the excitation frequency (25 kHz). The nonlinearity can be quantified by adding the amplitudes of all the visible nonlinear frequencies. This sum will be represented by variable HHSum.

For the VAM case the nonlinearity is difficult to be distinguished from the time domain signal. However, in frequency domain the nonlinear frequencies are visible around the probe frequency. These are known as side-bands and occur in pair at pump frequency ± multiples of pump frequency. In the current simulations, only the first pair of side-bands (100±5 kHz) are visible in the frequency spectrum. The nonlinearity will be quantified by adding the amplitudes of first side-band pair frequencies. This sum will be denoted by SBSum. The VAM Case has also been discussed in previous works [8].

For the SWP case the nonlinearity is in the form of area in the region of higher harmonic of the input signal. For our case the excitation signal is from 20-30 kHz, so the nonlinear frequencies occur in region 2x(20-30 kHz) = 40-60 kHz. The nonlinearity will be quantified by the area under the higher harmonic region and will be denoted by SumNonLin [9].

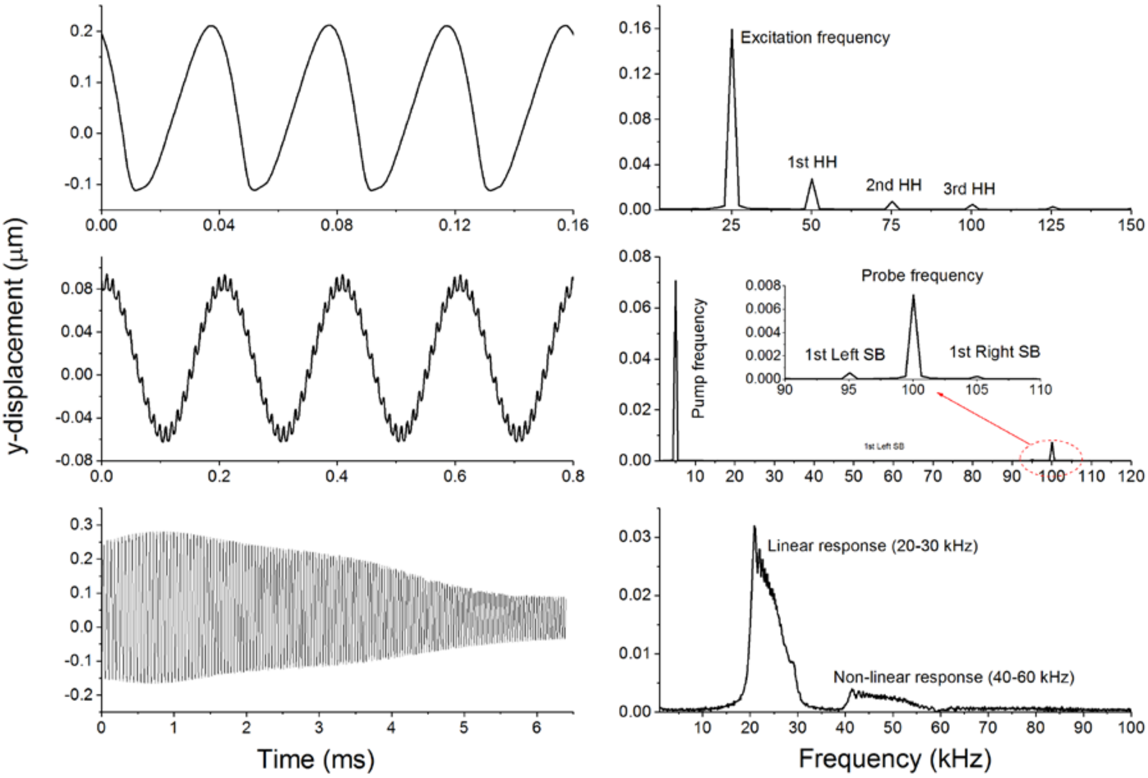

Figure 4: y-displacement at the output point in time domain (left) and frequency domain (right). *Top:* SFE; *Middle:* VAM; *Bottom:* SWP

In order to obtain the full field view of the nonlinearity the nonlinearity indices; HHSum, SBSum, and SumNonLin described for the three signals; SFE, VAM, and SWP are plotted on the top surface of the plate (Figure 1). The plot is shown in Figure 5.

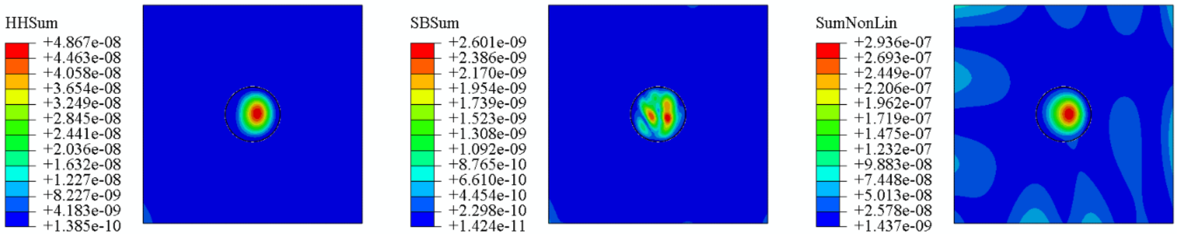

Figure 5: Damage mapping for different excitation signals on the top surface of the plate. Left: SFE; Middle: VAM; Right: SWP

It can be seen that plotting the amplitudes of the nonlinear frequencies over the top surface of the plate can predict the area of delamination up to a certain extent. The nonlinear methods do not provide a very distinct boundary between the damaged and intact portions of the plate and the nonlinear values are maximum in the delamination and then decreases gradually towards the intact portions. The distribution of the nonlinear amplitudes is also different for the three excitation methods. Due to limitations of the plotting algorithm the values are not zero but lesser in intact regions.

3.2 Parametric studies

In order for the nonlinear methods to be robust they need to be checked for a large number of delamination scenarios to evaluate whether they will work for all the delamination cases. For this purpose, the above model has been extended and converted into a parametric model which provides the option to test the nonlinear methods in many scenarios. This section studies the influence of depth, diameter, and position of the delamination on the imaging capability of the nonlinear methods. The cases with dual delaminations will also be discussed.

3.2.1 Delamination depth

The depth of the delamination is varied from 0.3 mm by 0.1 mm (0.2 mm and 0.4 mm) to study its influence on the damage mapping. The results from these simulations are shown in Figure 6. The damage imaging results from previous base case with 0.3 mm depth of the delamination (Figure 5) have also been plotted to mark the differences between nonlinear imaging for different delamination depths more clearly.

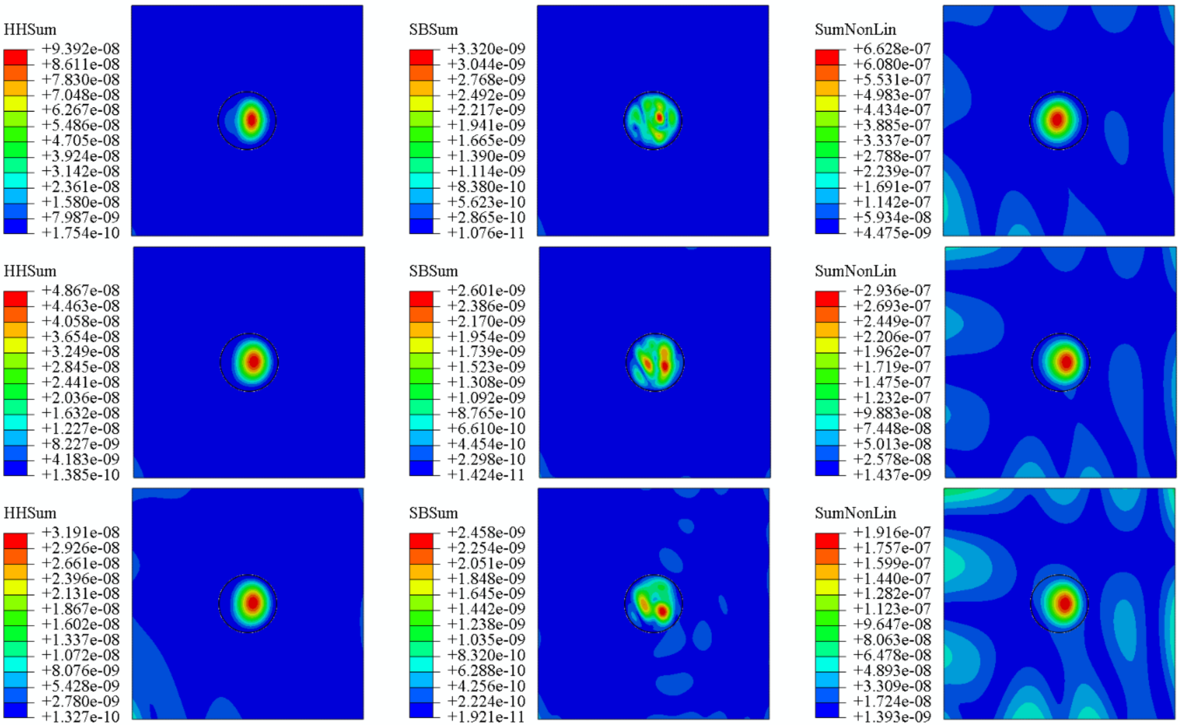

Figure 6: Effect of delamination depth on the nonlinear damage imaging methods. *Top:* 0.2 mm; *Middle:* 0.3 mm; *Bottom:* 0.4 mm

It can be observed from Figure 6 that the amplitude of the nonlinear frequencies HHSum, SBSum, and SumNonLin for the three excitation signals SFE, VAM, and SWP respectively increases when the depth of delamination increases. Also, the quality of the mapping decreases with the delamination depth as the nonlinear frequency amplitudes decrease. Therefore, it can be concluded that the delaminations closer to the surface are easier to diagnose in comparison to the ones deep inside the composite laminates.

3.2.2 Delamination diameter

To evaluate the effect of delamination diameter on the nonlinear damage imaging the simulations are performed for two more values of delamination diameters i.e. 9 mm, and 10 mm in addition to the 10 mm delamination diameter. These results have been shown in Figure 7 and include the results for 10 mm delamination diameter case previously shown in Figure 5.

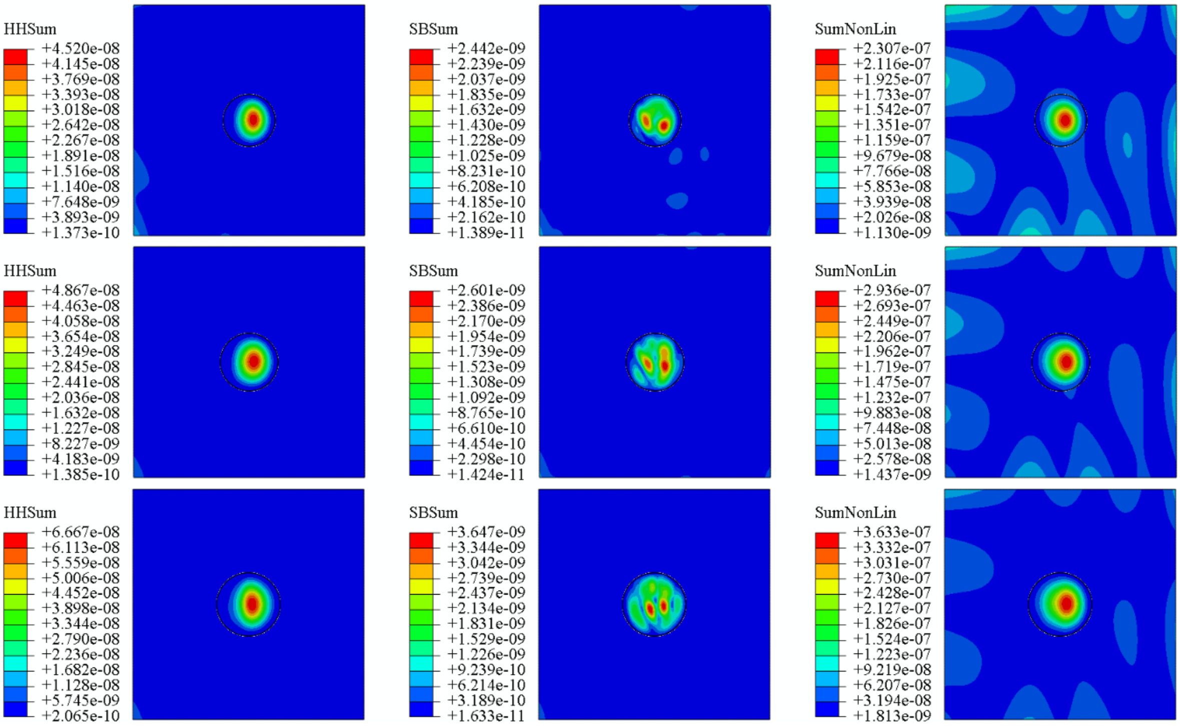

Figure 7: Effect of delamination diameter on the nonlinear damage mapping. *Top:* 9 mm; *Middle:* 10 mm; *Bottom:* 11 mm

It can be seen that the maximum amplitude of the nonlinear frequencies for all the three cases increases as the delamination diameter increases from 9 mm to 11 mm. The area of the region in which the amplitudes of nonlinear frequencies are higher also increases with the delamination diameter. Therefore, it can be concluded that the nonlinear imaging methods are sensitive to the diameter of the delamination and it is easier to detect larger delaminations in comparison to the smaller ones.

3.2.3 Delamination position

More simulation studies are performed by moving the delamination from the center of the plate to different locations as shown in Figure 8. It can be observed that the nonlinear damage mapping provides different results when the delamination position is different from the center. However, for all of the cases the delamination could still be picked up by the nonlinear methods.

It is to be noted that when the delamination is farthest from the excitation source the SFE and SWP methods do not provide a very clear indication of the damage mapping. It is due to the fact while SFE uses frequency of 25 kHz and SWP also uses frequency in range 20-30 kHz, VAM contains higher frequency component of 100 kHz as probe frequency. Different frequency waves travel with different characteristics and this will have an effect on the nonlinear imaging processes.

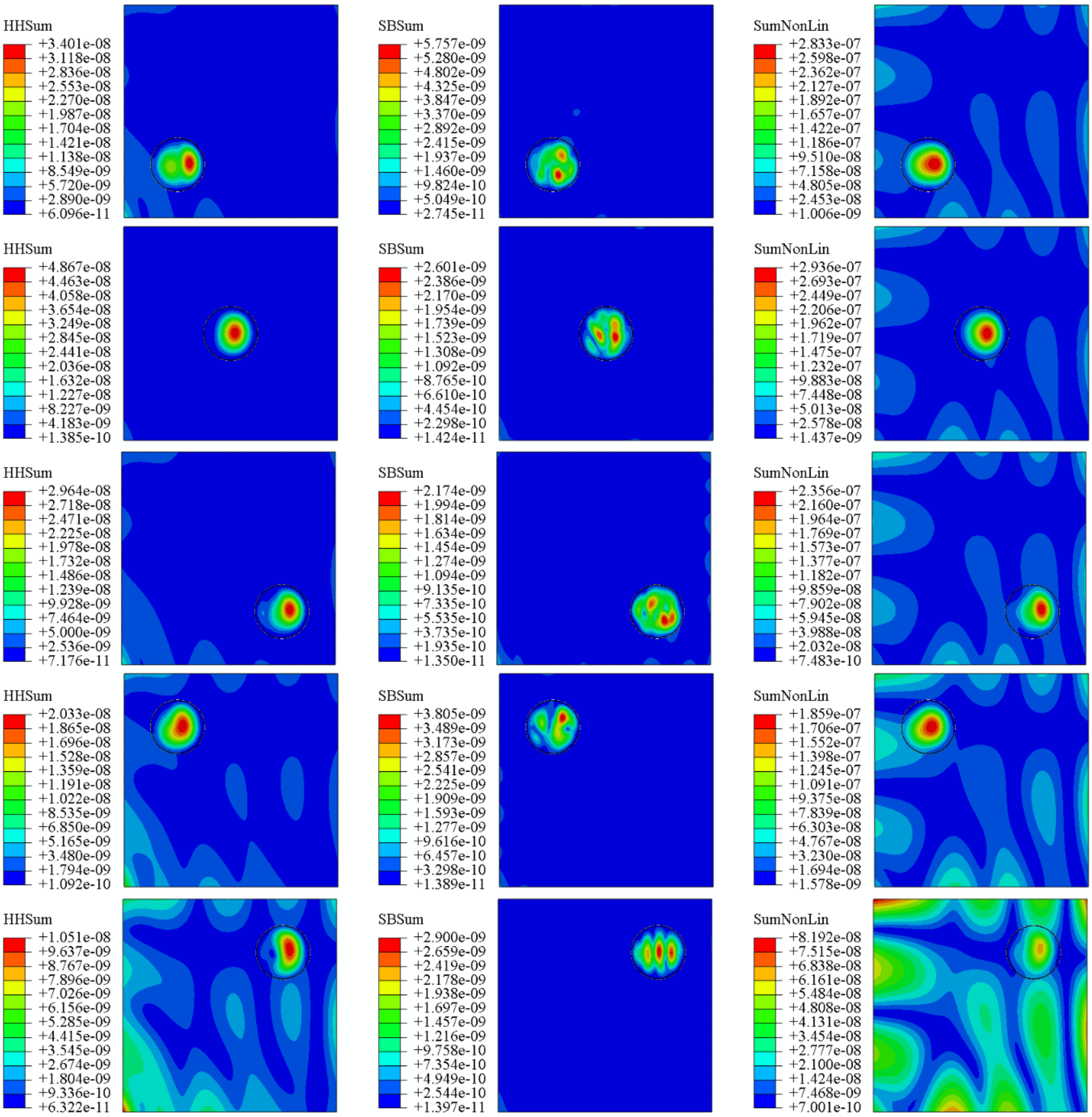

Figure 8: Effect of delamination position on the nonlinear damage imaging.

3.2.4 Multiple delaminations

To assess whether the nonlinear methods could capture the cases with multiple delaminations, simulations are performed with one delamination in the center and changing the position of the second delamination as in previous section 3.2.3. The results from these simulations are shown in Figure 9.

It can be observed that the two delaminations have significantly different amplitudes of nonlinear frequencies in the corresponding delamination regions. However, both delaminations could be roughly identified for all the cases. In these simulations also, the delamination which is farther from the excitation source provides lesser amplitudes of the nonlinear frequencies.

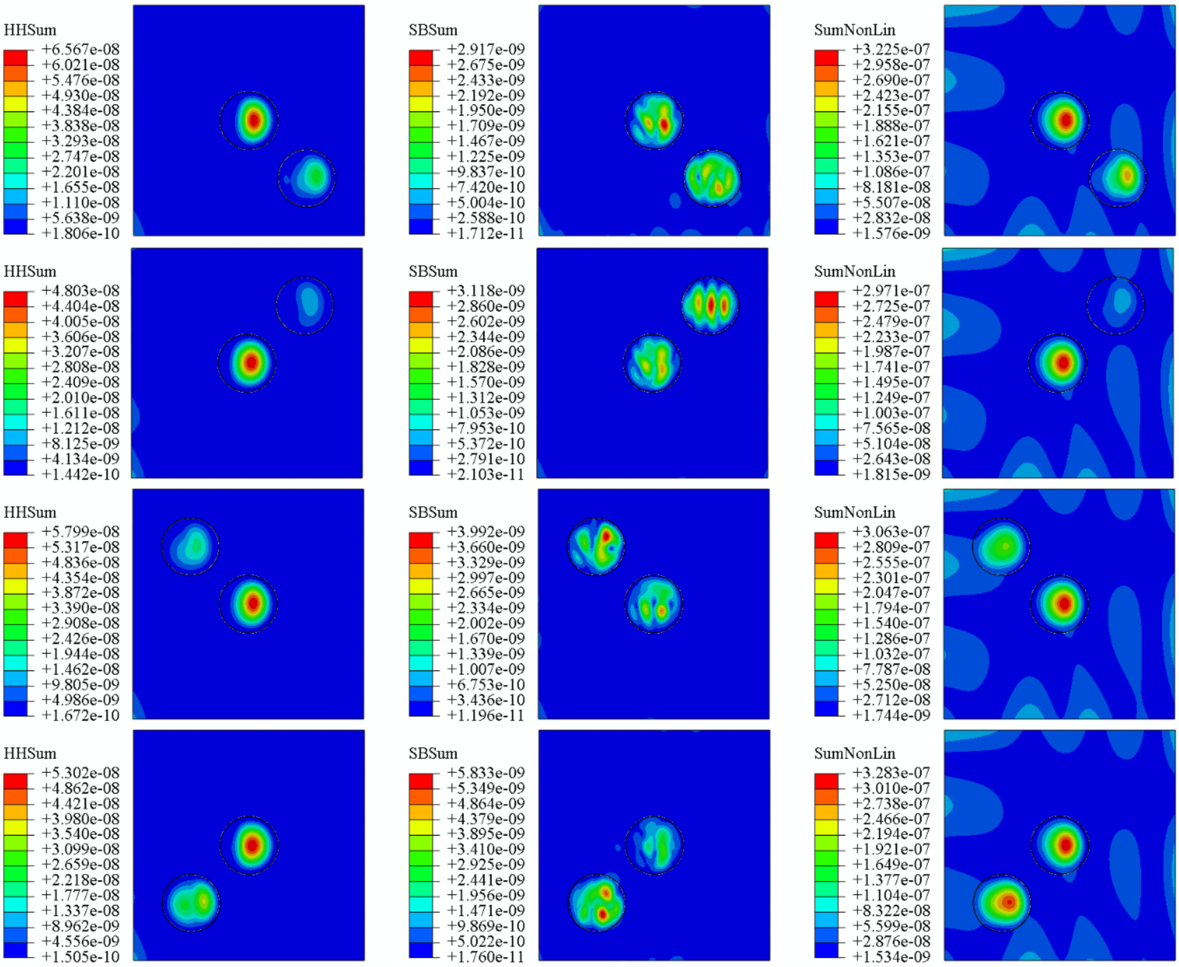

Figure 9: Effect of multiple delaminations on the nonlinear damage imaging.

4 CONCLUSIONS

Based on the simulation results it can be concluded that the nonlinear acoustic methods can be used for damage mapping in composite laminates. The following conclusions can be drawn from the parametric studies:

- Delamination depth: As the depth at which the delamination is inside the composite laminate, increases, the amplitude of nonlinear frequencies decreases and the nonlinear damage mapping becomes less efficient.
- Delamination size: The size of the delamination predicted by the nonlinear methods roughly corresponds to the size of the original delamination. However, the predicted area is lesser in comparison to the actual delamination area. Furthermore, different excitation signals would predict different delamination areas.

- Delamination position: The nonlinear methods can predict the delamination for different position of the delamination on the plate surface. However, the delamination areas predicted are different for different positions.
- Multiple delaminations: The detected delamination areas of two delaminations are different although they are of the same size.

For the future study, the simulation results will be used as references when experimental studies are conducted and the models will also be used to develop and improve the algorithms used to generate the damage mapping based on the nonlinear vibration signals. One further area of research is to get the damage mapping using minimum instrumentation with only a few piezoelectric sensors on the output surface.

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