8^{th} **European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2022)**
June 05- 09, 2022, Oslo, Norway

Investigation of Higher Harmonic Lamb Waves for Facilitating Delamination Characterization

Akhilendra S. Gangwar and Dhanashri. M. Joglekar*

Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee 247667, India
dhanashri.joglekar@me.iitr.ac.in

ABSTRACT

We advance this field by systematically exploring nonlinear interactions of A0 Lamb mode signals with delamination defects of various sizes and interlaminar locations, to facilitate the characterization of delaminations. The interrogation signal, in this regard, is a modulated sinusoid whose frequency varies in steps of 20 kHz between 40 kHz and 100 kHz. Commercial FEM software is used for modelling the contact at delamination interfaces and for simulating the Lamb wave propagation through the waveguide with delamination defect. It is demonstrated that the intermittently acting contact pressure between the two surfaces of delamination acts as a source of nonlinearity, resulting in generation of higher order harmonics of interrogation frequency. A metric for measuring nonlinearity, the nonlinearity index (NI), is used to quantify the strength of wave-damage interactions over a range of interrogation frequencies. The NI index is observed to vary with both the interlaminar location as well as the width of the delamination. The maximum value of NI is further influenced by the frequency of excitation signal. To infer the effect of delamination parameters on the NI, a concept of a concept of contact energy intensity is introduced, which is largely dependent on the size and the interlaminar position of the delamination. The nonlinearity index patterns are explained by combining the intensity of the contact energy with the phase difference between waves traveling through the sub-laminations and the flexural rigidity of the two sub-laminates at the delamination location. The inferences provided can potentially be used for determining the interlaminar location and width of delamination employing higher harmonic Lamb wave signals generated by the breathing delamination.

Key words: Lamb wave, Composite laminate, Through-width delamination, higher harmonics

1 Introduction

Recent advancements in manufacturing techniques have given FRP composites a wider range of applications in the aerospace, civil, and mechanical industries [1-5]. However, their susceptibility to various defects necessitate frequent inspection for ensuring the safety and reliability of these structures. On the downside, laminated composites a critical defect known as delamination occurs, leading to catastrophic structural collapse [6]. Delamination occurs inadvertently in laminated composites between the interfaces of any adjacent plies because to greater inter-laminar stresses. Regular inspection is required to overcome these issues.

In this regard, the Lamb wave based Non Destructive Techniques (NDT) are considered as one of the most viable methods to be employed for inspecting long composite panels, for the ability of these waves to propagate over longer distances and to scan the entire thickness. Recent years have seen a rise in the use of Lamb wave-based techniques for composite plate NDT. Delamination can be detected and characterized by linear Lamb wave methods that take advantage of properties of the wave signal in the time domain. Researchers have studied Lamb waves and delamination for more than a decade with the aim of improving damage detection in laminated structures. As delamination is one of the predominant mode of defect in FRP composites, many researchers have investigated the Lamb wave interactions with the delamination for facilitating the localization and characterization of delamination. Linear Lamb waves multimodal dispersion characteristics make it challenging to model temporal and geometrical constraints for the detection and characterization of incipient and tiny defects [8-10].

Nonlinear detection methods can detect such damage more reliably than linear Lamb wave detection [11-14]. They have emerged as serious candidates to be used as damage precursors due to the improved sensitivity of the response characteristics emerging from nonlinear wave-damage interactions [15]. These interaction of Lamb waves with defects like delamination in composite plates to produce nonlinear harmonics. These harmonics can be used as a good early diagnostic of even tiny delaminations [16-19]. Researchers have recently focused on nonlinear harmonic production in the frequency domain in order to determine the magnitude and location of delamination in composite plates. The intermittent contact between the surfaces at the delamination (known to as a "breathing of the delamination") is one of the prominent mechanisms that generates such nonlinear.

The nonlinear interactions of Lamb wave signals with eight-layered glass fiber reinforced plastic (GFRP) composite plates were examined in this study, with different delamination sizes and interlaminar locations. Numerical analysis was performed on $[0]_8$ GFRP composite plates with delaminations variations in steps of 2 mm between 8 mm and 16 mm in different interlaminar locations in order to investigate the effects of delamination size on nonlinear harmonics. As sub-laminates open and close in the delaminated region, nonlinearity is caused, resulting in contact acoustic nonlinearity (CAN). The size and the interlaminar position of the delamination affect the nonlinear harmonics. Based on the simulated results, a comprehensive parametric research was done to determine the impact of delamination size on nonlinearity. The remainder of the paper has been divided into three parts. Section 2 discusses FE modelling as well as contact couples. The results are thoroughly reviewed in part 3, and the conclusion is summarised in section 4.

2 Numerical Framework

ANSYS 19.0 was used to model the thickness direction of GFRP composites. As illustrated in figure 1, the 2D model has a dimension of 450 x 4 mm^2 and is made up of 8 laminas of thickness 0.5 mm. The material properties of the 0° lamina are shown in Table 1. The laminated composite plate is simulated using 2D (PLANE82) element considering plane strain conditions. After meshing the composite plate, nodes in the same location in different layers must be merged to ensure proper bonding between them. To construct a delamination between two layers, nodes at the surfaces should stay unmerged.

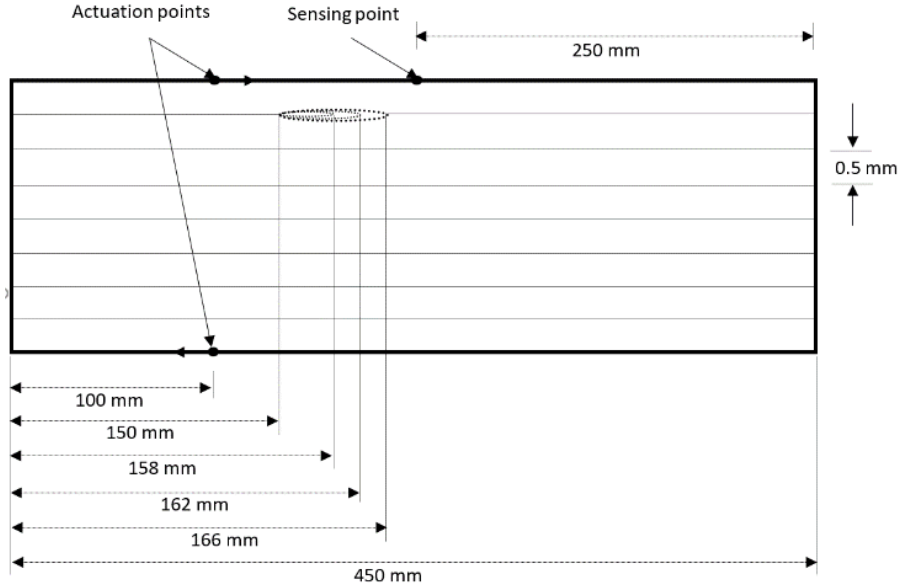
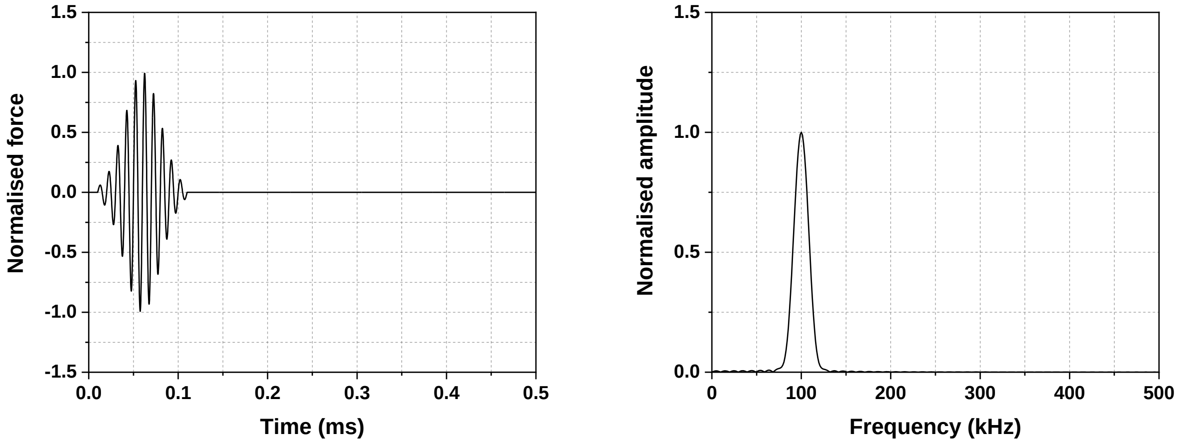


Fig. 1 GFRP composite laminate with different size of delamination defect.

Table 1. Material Properties of GFRP laminated composite plate

Material	E_{11} (GPa)	E_{22} (GPa)	G_{13} (GPa)	G_{23} (GPa)	υ_{13}	υ_{23}	ρ(Kg/m^3)
GFRP	44.68	6.90	2.54	2.5459	0.28	0.355	1990

As shown in figure 1, at the actuation points of top and bottom nodes, a transient force of an in-plane tone burst signal in the opposite direction is applied to generate the A0 Lamb mode. A MATLAB code is written to generate the excitation force file for a time step of 100 ns and a total of 0.5 ms. It is more important to keep the excitation time constant than the number of cycles.



(a) (b)

Fig. 2 100 kHz input excitation signal (a) time domain, (b) its frequency spectrum

Figure 2 shows the 100 kHz excitation signal in both time and frequency domain. In numerical simulation, mesh size is critical. An FE simulation should be accurate enough to have a mesh size that has at least 20 nodal distances per wavelength distance. In this simulation, interrogation frequencies were 40, 60, 80, and 100 kHz, with some additional frequencies resulting from contact acoustic nonlinearity (CAN). A simulation would determine the mesh size based on the smallest wavelength in the waveguide. A Semi-Analytical Finite Element (SAFE) technique was used to calculate group velocities and wavelengths. All numerical simulations performed for this study used a very fine discretized mesh with an element size of 0.25 mm. The time step also a key factor in FE simulation accuracy. Because SAFE knows the group velocities for the different frequencies, it is easy to estimate the optimum time step using the CFL conditions. The time step resulting from the preceding condition is 0.1 µs.

$$\Delta t = \frac{L_{\min}}{C_{\max}} \tag{1}$$

ANSYS provides many ways for establishing contact pairs in finite element modelling, including the augmented Lagrange approach, the penalty method, and the direct method. The Augmented Lagrange (AL) approach was employed in this study because it enables better penetration control and governing equation validation while also taking less time to compute. During a series of iterations, these approaches adjust the normal penalty stiffness and penetration tolerance. The authors chose hard contact conditions to replicate the contact pair in these simulations since this minimises the slave surface's penetration into the master surface. In order to prevent penetration, both the surface of delamination must adjust their stiffness when they interact in the sublaminate zone. Delamination faces have been assigned the contact elements CONTA172 and TARGET169 as contact and target surfaces, respectively. Friction forces between the delamination faces were considered to be absent in this problem.

The passage of a wave through a delamination zone produces nonlinear interactions between sub-layers, which result in some additional frequency components. For the detection and characterization of delamination, nonlinear contact analysis requires a mathematical definition of nonlinearity. In the past, many researchers have developed their own CAN formulations. The wave energy ratio approach was used by many researchers [20-22], in which the energy of a harmonic is proportional to its amplitude in the frequency domain. In equation 2, A_i is the amplitude of the i^{th} harmonic in the Fast Fourier Transform (FFT) response of the signal.

$$NLI = \sqrt{\frac{A_2 + A_3 + A_4 + \ldots}{A_1}}. \tag{2}$$

Result and Discussion

Different aspects of delamination detection can be determined from the nonlinearity trends produced from numerical simulations using nondestructive evaluation of structures. The nonlinear interactions of Lamb wave signals of various sizes and interlaminar positions of delamination defects were studied using the aforementioned finite element framework. Composite laminates with the stacking sequence $[0]_8$ are researched for this purpose.

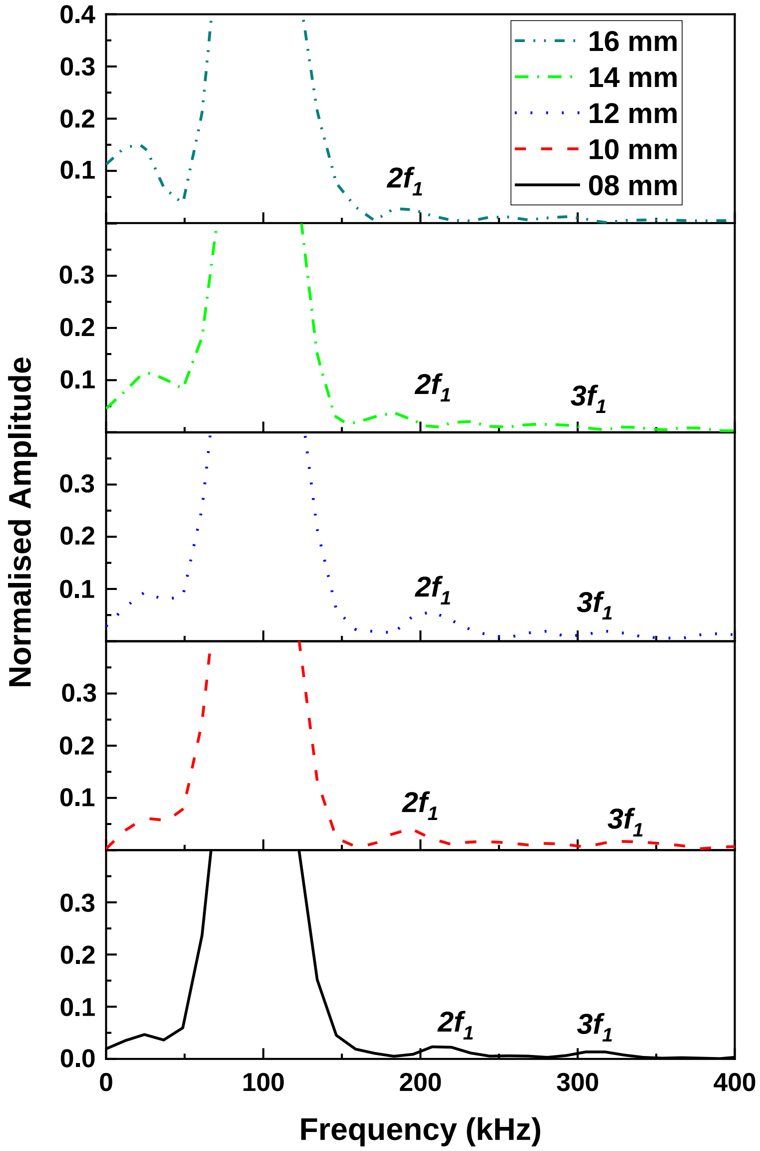


Fig. 3. FFT response for the GFRP composite laminate with different size of delamination

Two criteria, the size and location of the delaminations, must be understood to characterise the nonlinearity trends on the laminate with delaminations. The influence of delamination size and interlaminar position on nonlinearity index is investigated in this study using five different delamination examples at varied interfacial positions. Utilizing a 100 kHz actuation signal and delamination at various interfacial points, a series of numerical simulations using the FE approach for A0 wave propagation were undertaken. For each temporal response, the FFT response was determined. Additionally, Eq. 2 is used to enumerate the nonlinearity index. Studies of signal receiving locations have also been conducted, and it has been discovered that the nonlinearity patterns are unaffected by the sensor's location. Sensing locations are chosen at a distance of 50 mm from the leading edge of the delamination for consistency. Pitch-catch based A0 Lamb mode actuation and signal reception are considered in this study.

Figure 3 depicts the FFT response for various delamination diameters between the first and second layers. Higher harmonics are recorded, and the nonlinearity index peaks at a particular delamination limit before declining. The FFT response of various inter-laminar regions at 12 mm delamination is shown in Fig. 4. Higher harmonics are found and reduce as the interfacial position of delamination shifts from edge to center.

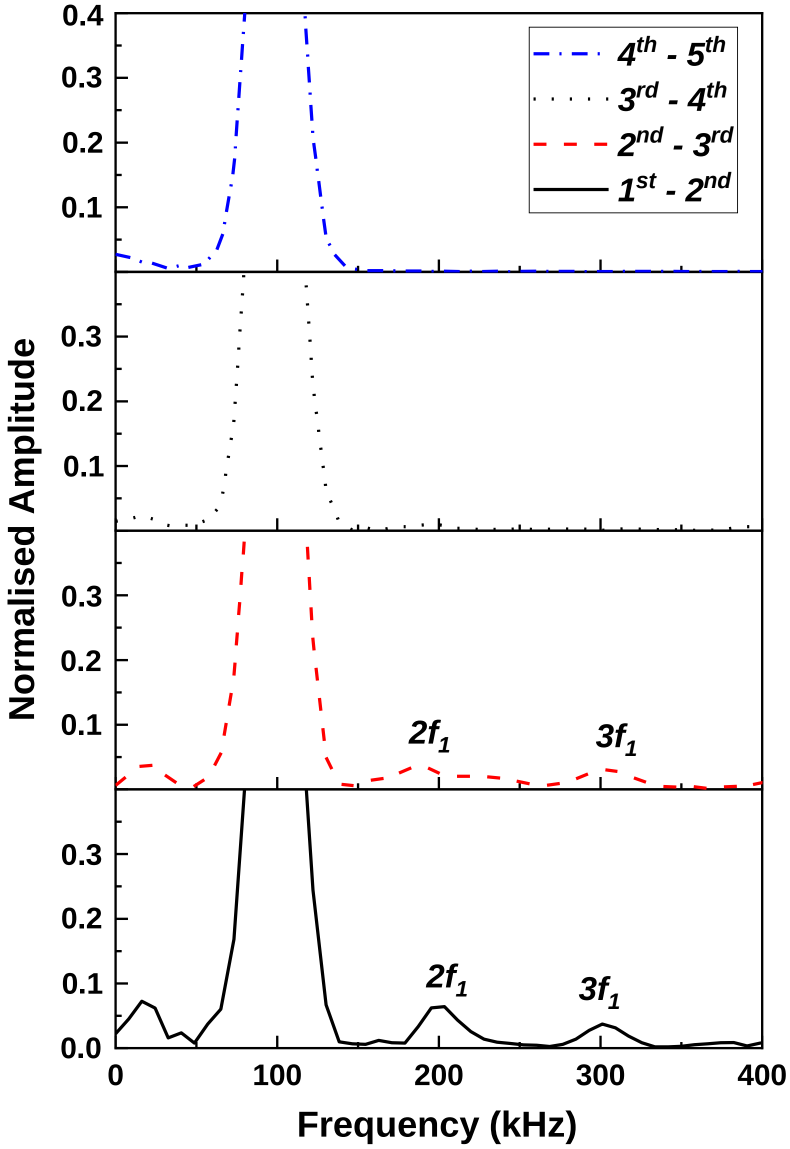


Fig. 4 FFT response of various inter-laminar location of 12 mm delamination.

As shown in figure 5, as we proceed from the leading edge of delamination to the trailing edge of delamination, the phase difference between the sublaminates grows, causing nonlinearity. Figure 6. displays the transverse displacement at various interlaminar points at the midpoint of delamination. The flexural rigidity difference between the two sublaminates decreases as we move centre of GFRP composite plate, which makes nonlinearity stronger. The nonlinearity index is thus impacted by two significant elements. The nonlinearity index was generated for all examples in order to investigate the relative strength of higher harmonics under various settings. Figure 7 depicts the non-linearity index's trend with different delamination sizes.

The NLI is at its highest for the 12 mm delamination at 100 kHz. This pattern can be explained by a variety of factors that influence contact nonlinearity in general, such as the phase difference between wave motion in delamination surfaces. The phase difference in the delamination region grows as the difference between the phase velocities of waves grows. Due to the sub-laminate thickness, the phase difference between sub-laminates reduces as the other delamination approaches towards the centre. The same process can be used to explain the nonlinearity trend for different delamination overlaps. More sub-laminate regions will be created as the overlapping increases, reducing the relative thickness and phase difference between the sub-laminates.

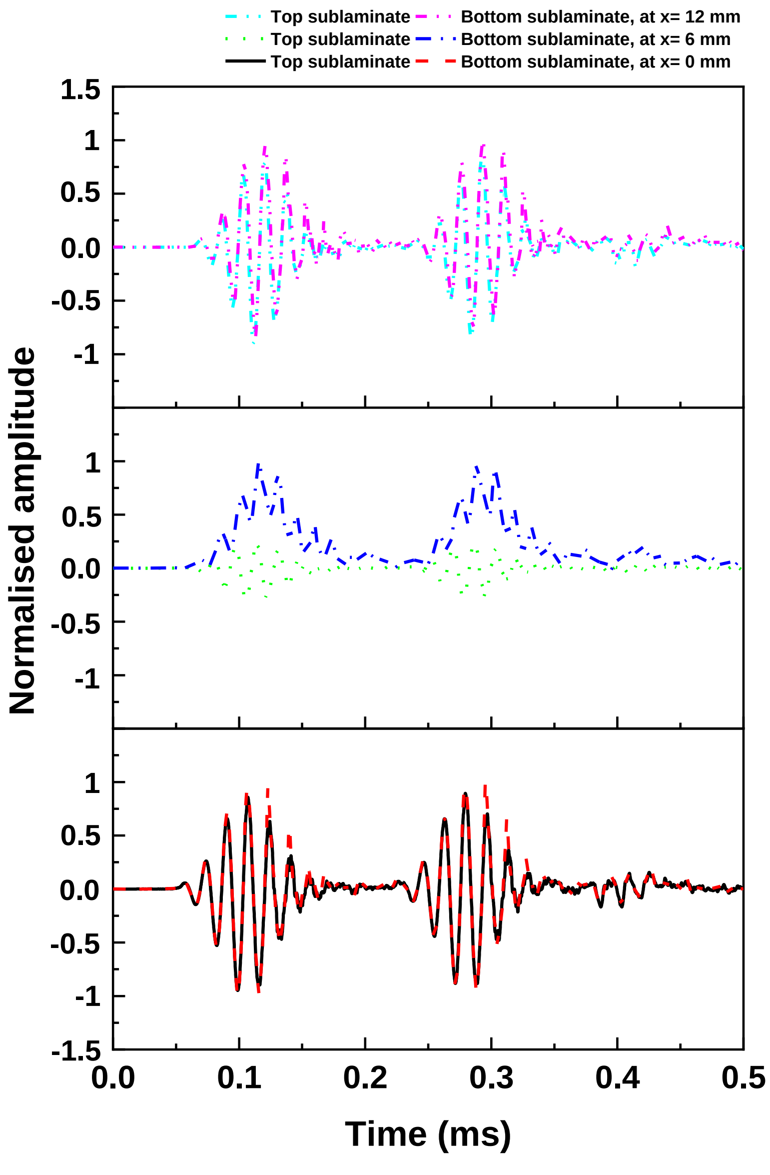


Fig. 5 Transverse displacement at different point of displacement at 100 khz for 12 mm delamination placed between 1st and 2nd layer.

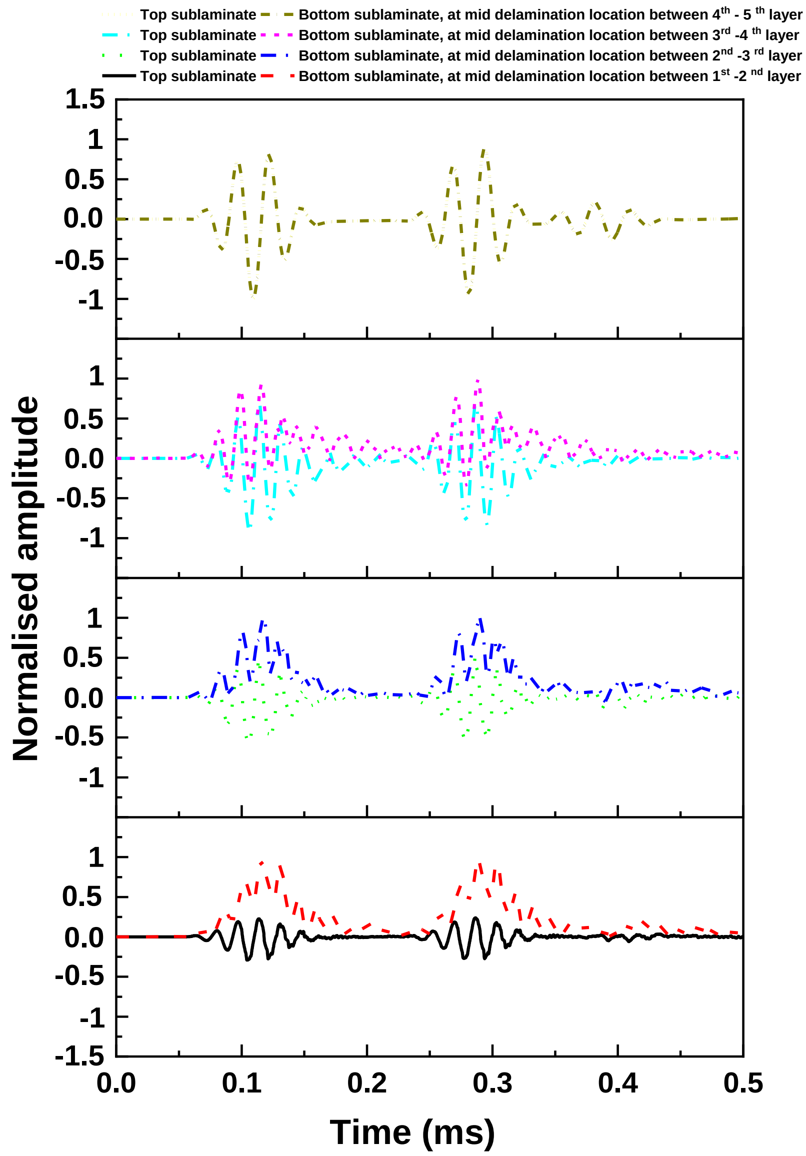


Fig. 6 Transverse displacement at various interlaminar position of delamination.

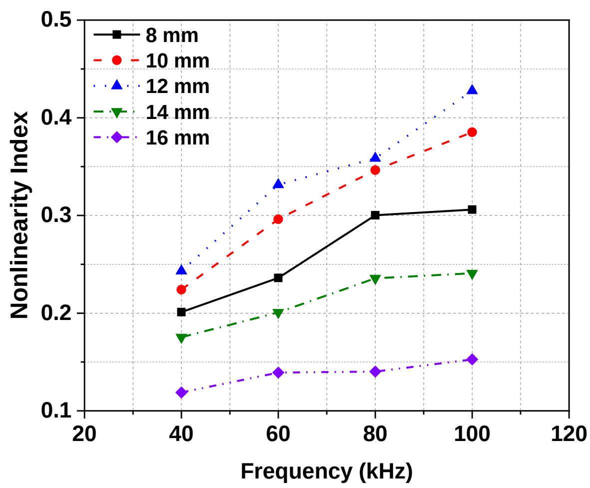


Fig. 7 NI variations with frequency of excitation, for delamination located at 1-2 interface.

4 Summary and conclusions

The higher harmonics are generated by the nonlinear interaction of the Lamb wave signal with the delamination, it is concluded. Higher harmonics are generated by the CAN depending on the amount of the delamination, according to the FE simulation study. The size of the delamination has been varied between 8 and 16 mm. It has been discovered that nonlinearity grows until a specific delamination limit is reached, after which it decreases. Nonlinearity caused by delamination has also been addressed and judged to be mostly dependent on the phase difference and laminate thickness. It was also discovered that the phase difference is directly proportional to the phase speed difference between sub-laminates at the delamination site. The findings of this work suggest that nonlinearity patterns can be used to develop a method for identifying and characterizing delamination during nondestructive testing. Furthermore, the strength of nonlinear harmonics appears to be dependent on the interlaminar location and extent of the delamination, according to this research.

Acknowledgements

The authors are grateful for the financial support provided by the Indian Institute of Technology Roorkee, India.

REFERENCES

1. Mitra, Mira, and S. Gopalakrishnan. "Guided wave based structural health monitoring: A review." Smart Materials and Structures 25.5 (2016): 053001.
2. Giurgiutiu, V. (2015). Structural health monitoring of aerospace composites.
3. Munian, R. K., Mahapatra, D. R., & Gopalakrishnan, S. (2018). Lamb wave interaction with composite delamination. *Composite Structures*, *206*, 484-498.
4. Mitra, A. K., and Joglekar D. M. "Numerical Investigation of Adiabatic Behaviour of Guided Waves in a Honeycomb Composite Sandwich Structure." *AIAA SCITECH 2022 Forum*. 2022.
5. Khurana, A., Sharma, T., and Shukla K. K. "Analysis of Thin walled composite box beam with and without piezoelectric actuators using ABAQUS." *Proceedings of the third Indian conference on applied mechanics*. 2017.

6. Feng, B., Ribeiro, A. L., & Ramos, H. G. (2018). Interaction of Lamb waves with the edges of a delamination in CFRP composites and a reference-free localization method for delamination. *Measurement*, *122*, 424-431.
7. Guo, N., & Cawley, P. (1993). The interaction of Lamb waves with delaminations in composite laminates. *The Journal of the Acoustical Society of America*, *94*(4), 2240-2246.
8. Ramadas, C., Balasubramaniam, K., Joshi, M., & Krishnamurthy, C. V. (2009). Interaction of the primary anti-symmetric Lamb mode (Ao) with symmetric delaminations: numerical and experimental studies. *Smart Materials and Structures*, *18*(8), 085011.
9. Gupta, S., & Rajagopal, P. (2018). Effect of ply orientation and through-thickness position of delamination on the reflection of fundamental symmetric S0 Lamb mode in GFRP composite plate structures. *Ultrasonics*, *90*, 109-119.
10. Gangwar, A. S., Agrawal, Y., and Joglekar, D. M. "Nonlinear interactions of lamb waves with a delamination in composite laminates." *Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems* 4.3 (2021).
11. Agrawal, Y., Gangwar, A. S., and Joglekar, D. M. "Mixing of lamb waves at delamination defect in a unidirectional gfrp laminate." *Advances in Non-destructive Evaluation*. Springer, Singapore, 2021. 317-328.
12. Jhang, K. Y. (2009). Nonlinear ultrasonic techniques for nondestructive assessment of micro damage in material: a review. *International journal of precision engineering and manufacturing*, *10*(1), 123-135.
13. Gangwar, A. S., Agrawal, Y., and Joglekar, D. M. "Nonlinear frequency mixing in gfrp laminate with a breathing delamination." *European Workshop on Structural Health Monitoring*. Springer, Cham, 2020.
14. Soleimanpour, R., Ng, C. T., and Wang, C. H., 2017. “Higher harmonic generation of guided waves at delaminations in laminated composite beams”. Structural Health Monitoring,16(4), pp. 400–417.
15. Agrawal, Y., Gangwar, A. S., and Joglekar, D. M. "Localization of a Breathing Delamination Using Nonlinear Lamb Wave Mixing." *Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems* 5.3 (2022): 031005.
16. Pieczonka, L., Klepka, A., Staszewski, W. J., & Uhl, T. (2014, July). Nonlinear acoustic imaging of structural damages in laminated composites. In *EWSHM-7th European workshop on structural health monitoring*.
17. Yelve, N. P., Mitra, M., & Mujumdar, P. M. (2014). Higher harmonics induced in lamb wave due to partial debonding of piezoelectric wafer transducers. *NDT & E International*, *63*, 21-27.

18. Nagaraj, M. H., Carrera, E., & Petrolo, M. (2020). Progressive damage analysis of composite laminates subjected to low-velocity impact using 2D layer-wise structural models. *International Journal of Non-Linear Mechanics*, *127*, 103591.
19. Agrawal, Y., Gangwar, A. S., and Joglekar, D. M. "Effect of Ply Orientation on Nonlinear Lamb Wave Delamination Interactions in GFRP Composite Laminates." *Advances in Non Destructive Evaluation*. Springer, Singapore, 2022. 423-434.
20. Shen, Y. (2017, April). Numerical investigation of nonlinear interactions between multimodal guided waves and delamination in composite structures. In *Health Monitoring of Structural and Biological Systems 2017* (Vol. 10170, pp. 397-407). SPIE.
21. Gangwar, A. S., Agrawal, Y., and Joglekar, D. M. "Effects of Delamination on Higher Harmonics Generation in Unidirectional GFRP Laminate." *Advances in Non Destructive Evaluation*. Springer, Singapore, 2022. 411-421.
22. Joglekar, D. M. (2020). Analysis of nonlinear frequency mixing in Timoshenko beams with a breathing crack using wavelet spectral finite element method. *Journal of Sound and Vibration*, *488*, 115532.