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Baseline-Free Characterisation of a Delamination using Nonlinear Vibro-Acoustic Modulation

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Abstract
Conventional non-destructive evaluation techniques based on linear response are less sensitive to micro-damage than large defects. Nonlinear ultrasonics has recently attracted strong interest as offering the potential of baseline-free early damage detection. In the present work we employ the nonlinear vibro-acoustic technique, where a structure is simultaneously subjected to a low frequency and a high frequency excitation in order to generate nonlinear vibrational responses for the characterisation of delamination damage. In the presence of structural damage such as cracks and delamination, nonlinear mechanisms such as contact acoustic nonlinearity are activated, resulting in the generation of sideband frequency components that are not generated in a pristine structure. Though extensive qualitative analysis has been performed to assess vibro-acoustic modulation techniques for detecting the presence of defects, there is still a lack of understanding of the spatial sensitivity of the nonlinear response and hence of the prospects for locating and sizing damage. The results of the present study demonstrate that sideband frequency components generated by a delamination defect can be used to characterize the damage.

Key words: NDT, Nonlinear, Modulation, Vibration, Damage, Detection.

1 INTRODUCTION

Early damage detection is of considerable interest for effective management of structural integrity. For example, barely visible impact damage (BVID) due to low velocity impact can greatly reduce the load carrying capability and safety of laminated fibre composite structures. Linear ultrasonics have shown considerable success in detecting large defects such as open cracks but are insensitive to micro-cracks and BVID making early damage detection difficult.

Nonlinear ultrasonics has the ability to detect damage substantially smaller than linear techniques allowing for the prospect of early damage detection [1-3]. Previous research indicate that nonlinear techniques outperformed linear ones because nonlinear effects induced from small levels of damage can be significantly higher than those pertinent to undamaged structures [2, 4-6]. One of the most direct nonlinear effect is the generation of higher harmonics, which are integer multiples of the input frequency (fundamental harmonic). Cantrell and Yost [7] demonstrated that the nonlinear parameter, defined as the ratio between the second harmonic and the square of the fundamental harmonic, could increase by as much as 300% for cyclically loaded structures. This result showed that the nonlinear parameter could be a very sensitive indicator of the distributed damage state in structure. However, for a small and localized damage, the use of higher harmonics becomes difficult due to their small amplitude and because the contribution of the local defect cannot be separated from the nonlinear contribution of the electronic hardware or the surrounding material.

An alternative method is the nonlinear vibration modulation technique, which has the ability to detect small levels of localized damage. In a linear system, which corresponds to the non-damaged structure, the principle of wave superposition applies. Considering simultaneous excitations by two distinct frequencies, the net response of the linear system is the sum of the two input frequencies as shown in Figure 1a. In a nonlinear system however, the principle of wave superposition no long applies, and the interaction of waves of different frequencies results in new frequency components as shown in Figure 1b. These new frequency components, referred to as sidebands, correspond to the sum and the difference of the HF input and multiple of the LF input. In other words, side bands appear at discrete frequencies of $f_2 \pm nf_1$, where $n = 1,2,3,...$. Because these sidebands are not present in the pristine structure, a baseline response is no longer required as is in the case of linear damage detection [8].

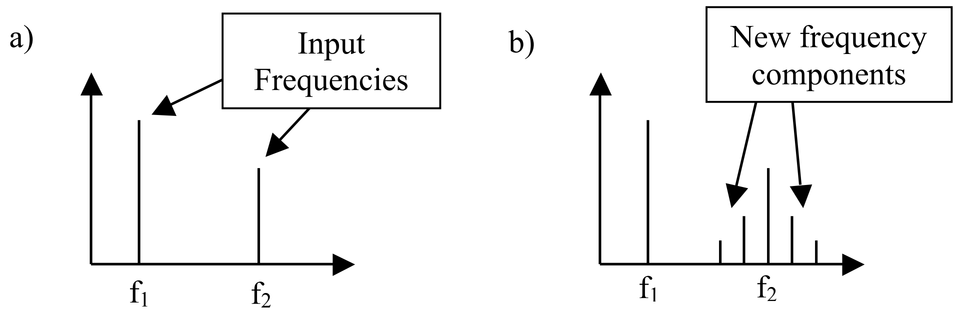

Figure 1: a) Linear system response showing only the two excitation frequencies and b) nonlinear system response showing the generation of new frequency components due to frequency mixing.

Consider now the case of a simple crack in a beam. When a low frequency vibration (also known as the pumping frequency) is applied, the crack can either be in an open or closed state depending on the phase as shown in Figure 2a. Assuming that the input load is strong enough to open and close the crack during the tension and compression phases, respectively [9]. Simultaneously, a high frequency wave (known as the probing frequency) is applied to the structure. During the compression phase the high frequency wave will transmit through the crack, whereas during the tension phase the high frequency wave is only partially transmitted, resulting in a decrease in amplitude. This results in the modulated signal show in Figure 2b. This modulated signal can contain various nonlinear features such as higher harmonics, sub-harmonics, mixed frequency components and/or sideband components which can indicate the presence of structural damage as these features are not present in a pristine sample.

This paper describes a numerical simulation study using nonlinear vibro-acoustic modulation on a simply-supported beam containing delamination damage to investigate the spatial nonlinearity distribution for damage characterization applications.

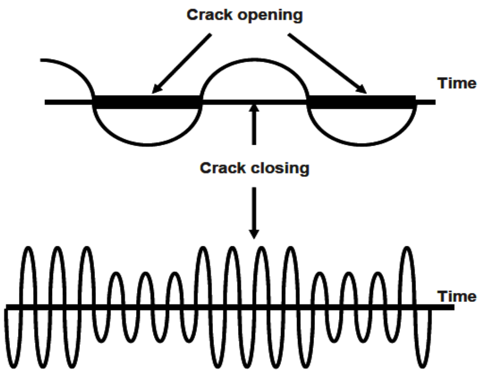

Figure 2: Amplitude modulation of probe signal: a) vibration, b) ultrasonic signal [3]

2 SIMULATION METHODOLOGY

2.1 FE Setup

A 2D model shown in Figure 3 was created using ABAQUS FE simulation software to model nonlinear vibro-acoustic modulation in a beam containing a delamination. The simply-supported beam model is isotropic homogenous and its properties are modelled based on aluminium with the geometry and dimensions shown in Table 1. Linear quadrilateral elements of type CPS4R were used with 4 elements through the thickness and 600 elements along its length.

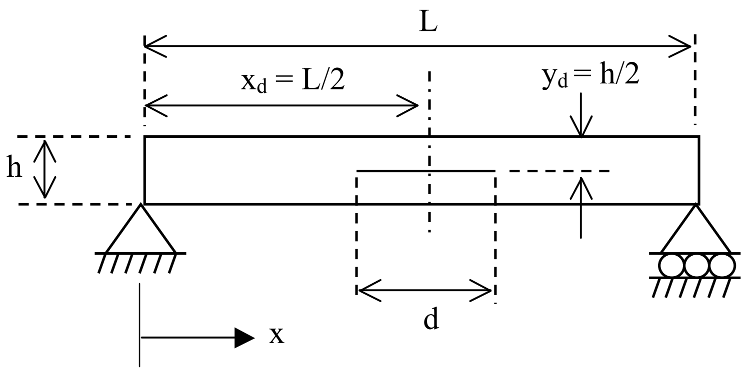

Figure 3: FE geometry and setup

The 20 mm delamination, d, is modelled by applying a seam and generating disconnected double nodes. Its centre is located at $x_d = 150$ mm and at depth $y_d = 1$ mm as shown in Figure 3. The nonlinearity considered in this delaminated beam is CAN. Therefore, contact conditions are implemented at the delamination and defined by the frictionless, hard contact condition in ABAQUS. This contact law prevents interpenetration between the two faces of the delamination.

Table 1: Beam dimensions and material properties

Length, L (mm)	**Height, h (mm)**	**Density, ρ (kg/m3)**	**Young's Modulus, E (GPa)**	**Poisson's Ratio**
300	2	2,760	69	0.33

3 FREQUENCY SELECTION

The mode shapes of the damaged beam were first determined using the ABAQUS linear perturbation analysis, which corresponds to a modal analysis. The Lanczos eigensolver was selected to extract mode shapes up to 50 kHz. Contact conditions are not considered in this step due to incompatibility with the solver. In other words, the crack faces were allowed to interpenetrate. This first analysis was carried out to obtain a first estimate of the different modal frequencies.

The resonant frequencies of the damaged beam with contact conditions were then calculated using an explicit, dynamic analysis. A sweep signal excitation, f, is applied at x = L/3 and the response is obtained at x as shown in Figure 4. The frequency sweep range was defined around modal frequencies determined in the previous step. From these computations, one modal frequency was selected for the LF, and two modal frequencies were selected for the HF. The resonant frequencies selected for nonlinear ultrasound modulation are summarised in

Table 2, where the modal frequencies obtained from the linear analysis, i.e without contact, are added for comparison. The introduction of the contact condition results in a resonant frequency increase between the two simulations.

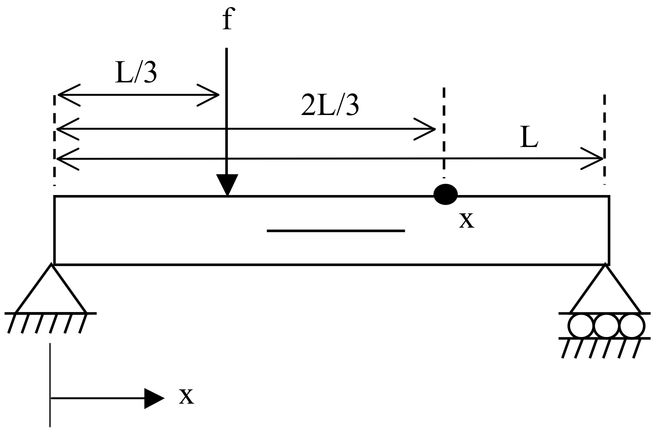

Figure 4: Dynamic, Explicit analysis loading conditions using sweep signal

Table 2: Delamination resonant frequencies and delamination location relative to operating deflection shape (Node/Anti-node)

Mode	**Linear perturbation analysis (Modal Analysis) Natural Frequency (Hz)**	**Nonlinear analysis (Explicit, Dynamic) Resonant Frequency (Hz)**	**Delamination Location (Node/Anti-Node)**
2	194	-	Node
17	10,441	10,474	Anti-Node
27	23,241	23,350	Anti-Node

4 NONLINEAR VIBRATION MODULATION

To generate sideband frequency components for the damaged beam, dual excitations were applied and crack surface contact was considered. Both a low frequency pumping signal, f_l

and a high frequency probing signal, f_2 was applied as shown in Figure 5. The applied load amplitude for the low frequency pump and the high frequency probe was 50 N and 10 N respectively.

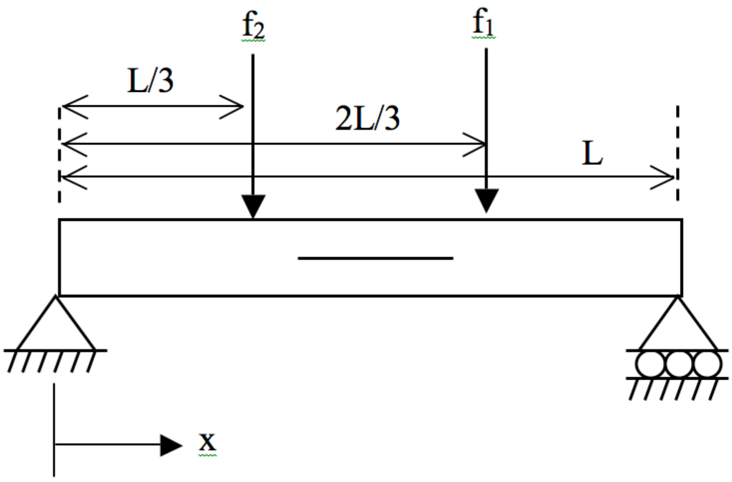

Figure 5: Loading conditions

To obtain the steady-state response and minimize transient effects, a ramp-up signal shape was used for both pumping and probing frequencies. An example is shown in Figure 6. To generate the signal, half a Hann window was applied to the first 0.2 seconds of the signal. Thereafter, a continuous sine wave was used.

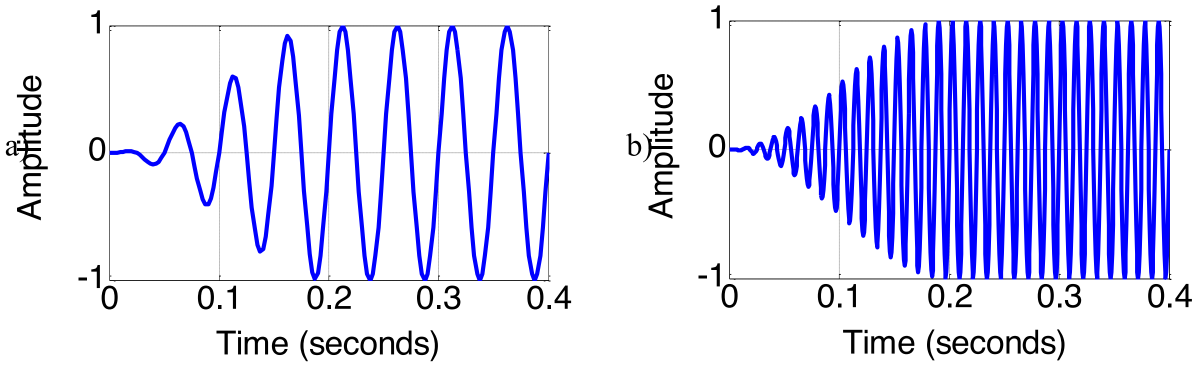

Figure 6: Ramp-up signal for a) low frequency pump and b) high frequency probe

5 SPATIAL NONLINEARITY DISTRIBUTION RESULTS

Nodal time-displacement information was extracted between the two loading positions at spacing of 2.5 mm to yield 21 measurement positions as shown in Figure 7.

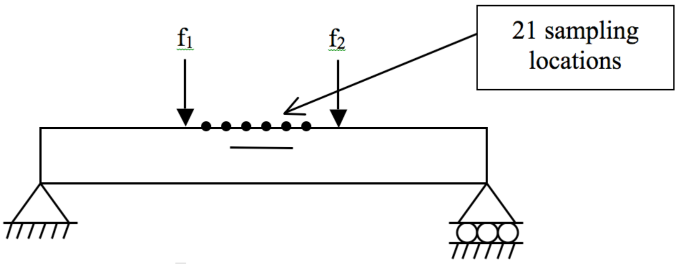

Figure 7: Measurement locations

A total of 500,000 time step data were extracted for each measurement location for the total signal duration of 0.4 seconds. A Hann window was applied on the recorded signals along with zero padding, followed by a Fast Fourier Transform to obtain the frequency response as shown in Figure 8. The lower and upper sideband components are clearly visible.

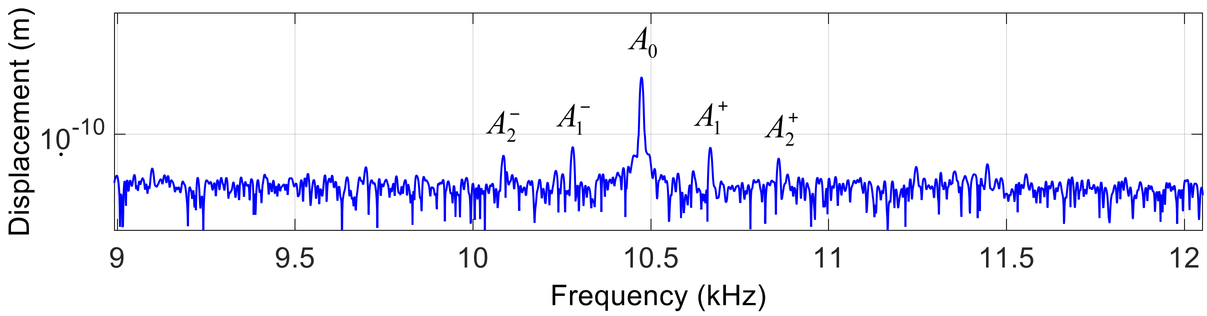

Figure 8: Frequency response about the probing signal with sideband frequency components present. Low frequency probing of 194 Hz and high frequency probe of 10,474 Hz

The spatial nonlinearity was mapped using the damage index, R, defined in equation 1 below.

$$R = \frac{A_1^- + A_1^+}{A_0} \tag{1}$$

where A_1^- is the amplitude of the first lower sideband, A_1^+ is the amplitude of the first upper sideband and A_0 is the amplitude of the high frequency probing signal at a fixed location (130 mm along the beam length in the x-direction). The frequency response was extracted at each measurement point and Equation (1) was applied, thus yielding the spatial nonlinearity distribution along the top surface of the beam, as shown in
Figure 9.

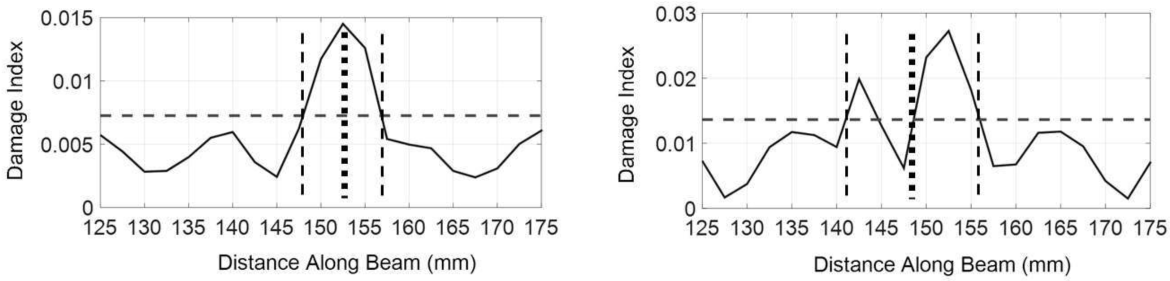

Figure 9: Spatial nonlinearity distribution along beam length for a) Low frequency = 194 Hz and high frequency = 10,474 Hz and b) Low frequency = 194 Hz and high frequency = 23,350 Hz

Results indicate that strong nonlinearity is generated near the centre of the beam for both plots. Delamination length is determined by measuring the length of peak in the beam direction at 50% of the maximum amplitude as indicated by the horizontal dashed line in Figure 9. The location of the delamination is defined as half of the predicted length position as indicated by the dotted vertical line. Results are summarised in Table 3 and Table 4 below.

Table 3: Prediction of delamination location (small delamination)

Low Frequency Pump (Hz)	**High Frequency Probe (Hz)**	**Actual (mm)**	**Predicted (mm)**	**Difference (mm)**
194	10,474	20	8.90	11.10
194	23,350	20	14.96	5.04

Table 4: Prediction of delamination location (large delamination)

Low Frequency Pump (Hz)	**High Frequency Probe (Hz)**	**Actual (mm)**	**Predicted (mm)**	**Difference (mm)**
194	10,474	150	152.41	2.41
194	23,350	150	148.49	1.51

Results indicate that use of a higher probing frequency provides a better length reconstruction. Both high frequencies used show excellent prediction of delamination location. Results also indicate that spatial nonlinearity due to the presence of a defect can be used for characterizing delaminations.

6 CONCLUSIONS AND RECOMMENDATIONS

Nonlinear vibro-acoustic modulation technique was applied to an isotropic, homogenous simply-supported beam structure with a delamination. Dual excitations were applied, composed of a low frequency pumping signal and a high frequency probing signal. These excitations were chosen to be the resonant frequencies of the damaged beam which were determined using an explicit, dynamic analysis frequency sweep. Results indicate that delamination damage can be detected using the vibro-acoustic modulation technique and that selection of the low and high frequency signals is an important parameter when characterising the damage (location and size). The results show that the damage index is significantly higher above the delamination. Prediction of delamination length was more accurate when using the higher mode for the high frequency probing signal. Determination of the delamination location was excellent for both high frequency probing signals used. Future work includes experimental verification and full parametric studies to investigate the use of various frequency combinations for both the low and high frequency excitations.

7 ACKNOWLEDGEMENTS

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