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Sideband Peak Count - a New Nonlinear Ultrasonic Technique for Monitoring Damage Progression in Engineering Materials

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Abstract
Linear ultrasonic (LU) techniques used by majority of the researchers working in material damage monitoring, are reliable for detecting relatively large defects. If the defect dimensions are in the range of the ultrasonic wavelength or larger, then those defects can be detected by analyzing the scattered ultrasonic fields. Material damage affects LU parameters such as ultrasonic wave speed and attenuation and their changes are detectable for relatively large defects. However, for small defects (when defect dimensions are significantly smaller than the wavelength of the propagating signal) the changes in the LU parameters are too small to detect or measure reliably. For detecting small defects engineers often use high frequency ultrasonic signals to make the defect dimensions greater than the wavelength. However, high frequency signals attenuate quickly and therefore, only very small regions near the ultrasonic probe can be inspected in this manner. Inspecting large structures by high frequency ultrasonic signals requires moving the probe mechanically from one point to the next and therefore, can be very time consuming.
Nonlinear ultrasonic (NLU) technique on the other hand does not need to satisfy this restricting condition that the wavelength of the signal must be smaller than the defect size. NLU works well when the signal wavelength is much larger than the defect size. Therefore, relatively low frequency signals that can propagate a long distance and monitor a large area of a structure can be used for NLU measurements.
Different NLU techniques can be used for detection and monitoring of small damages in a specimen. A relatively new NLU technique called the Sideband Peak Count-Index or SPC-I technique has been developed by the author and his collaborators. SPC-I technique for monitoring different types of materials – composites, metals, concrete, and other cement-based materials has been found to be effective. Along with those success stories of SPC-I the effect of topography and the advantage of topological sensing is also discussed in this presentation.

Keywords: Nonlinear Acoustics, Topological Sensing, SPC-I, Topography, Damage Detection

1. Introduction

Nonlinear ultrasonic (NLU) techniques are becoming more popular than conventional linear ultrasonic (LU) based techniques because of their effectiveness in monitoring damages at their early stages [1]. The newly developed NLU technique called sideband peak count – index (or SPC-I) has been successful in monitoring various types of damage in different materials, such as aging related damage in fiber reinforced cement mortar [2], fatigue cracks in metal parts [3], curing and damage monitoring in concrete [4-10], impact induced damage progression in fiber reinforced polymer composites [11-13], fatigue damage monitoring in welded joints of metal pipes [14], and porosity monitoring in additively manufactured metal parts [15, 16]. In addition to these experimental investigations [2-16], peri-dynamics and finite element based modeling for theoretical investigations have been also conducted to verify the experimental findings [17-22]. Recently some variations of the SPC-I technique called SPI and SII have been proposed and their performances have been compared with the SPC-I technique [23,24].

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In the SPC-I technique, sideband peaks are counted above a horizontal threshold line moving between a preset lower limit and an upper limit in the spectral plot. The SPC-I value is a measure of nonlinearity of the inspected specimen – larger SPC-I values indicates higher level of nonlinearity. The SPC-I technique shows many advantages over other well-established NLU techniques like higher harmonics generation (HHG) technique and nonlinear wave modulation spectroscopy (NWMS) method or frequency modulation (FM) method. For example, in HHG technique the guided wave mode selection criterion requires phase velocity and group velocity matching for the fundamental mode and the higher harmonic mode [25]. For heterohomogeneous engineering materials like composites and concretes the higher order harmonic components often are not clearly visible and hence it is difficult to apply this technique. The need of generating two precisely controlled distinct input wave frequencies for wave mixing makes NWMS/FM also comparatively more difficult technique to apply than the SPC-I technique [22]. In spite of all these advantages of the SPC-I technique, for defect detection in plates having complex topography SPC-I and other nonlinear/linear ultrasonic techniques sometimes encounter difficulty in detecting cracks. Then topological acoustics-based sensing technique has been found to be more effective [26]

2. Principles and methods

2.1 SPC-I technique

To generate SPC-I value for a material first a broadband ultrasonic signal is propagated through that material. The spectral plot of the signal after it propagated through the material and recorded by a receiver is obtained. A schematic diagram of the spectral plot of a received signal is shown in figure 1a. For the SPC-I analysis we count the peaks detected above a moving threshold line. The threshold line (the horizontal continuous line) is moved between two dashed lines which are two pre-set values - the lower threshold limit and upper threshold limit. All peaks which are above the moving threshold line and shown by the circles are counted and plotted against the threshold value in figure 1b. The SPC plot shown in figure 1b (number of peaks as a function of the threshold value) gives a visual representation of the degree of material nonlinearity. A material with higher nonlinearity should give higher SPC values compared to a linear material or a material having a lower level of nonlinearity.

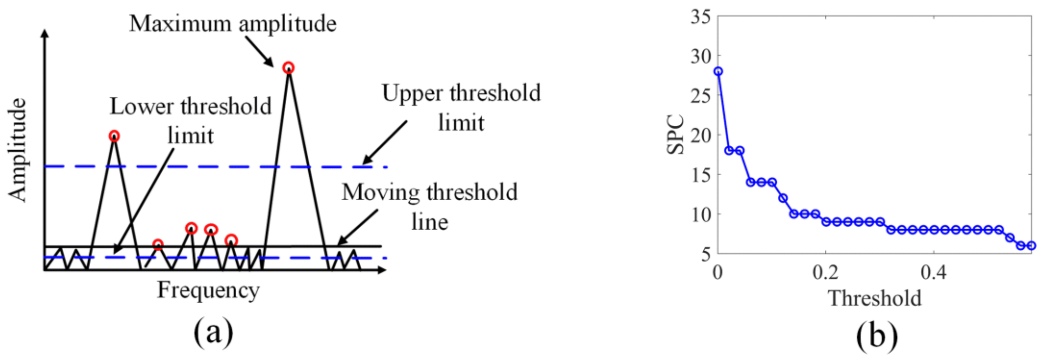

Fig. 1. Illustration of SPC. (a) Sideband peak counting and (b) example of SPC plot [17,18,21].

The SPC-I is a number or index which is calculated by taking the average of SPC values for all threshold positions shown in figure 1b. This SPC-I value indicates the degree of material nonlinearity, higher the material nonlinearity, greater is this number.

2.1 GPC technique

For topological acoustics based geometric phase change (GPC) technique acoustic signals are recorded at multiple points. Through appropriate signal processing the recorded signals are then transformed into a vector in a higher dimensional Hilbert space. The geometric phase of this higher dimensional vector in the Hilbert space is monitored as the material degrades. Readers are referred to Zhang et al [26] for a more detailed description about the geometric phase change computation.

3. Results and discussion

3.1 Comparison of SPC-I with other LU and NLU techniques

The superior performance of SPC-I method compared to other linear and nonlinear ultrasonic based techniques is illustrated in Figure 2. It shows very high sensitivity of the SPC-I technique to the micro level damage progression with load increment on the laboratory scale model of a bridge girder subjected to cyclic loadings [5]. Note that among all techniques presented here the SPC-I technique performs the best. Two very popular nonlinear techniques – higher harmonic (or super harmonic) technique and sub harmonic technique completely failed and did not produce any measurable data. Hence, the performances of super and sub harmonic techniques could not be even shown in this diagram. We can only say that they failed. Two best performing techniques are both nonlinear techniques: SPC-I and Energy distribution techniques. For each of these techniques the waves were propagated along two paths shown by continuous lines and dashed-dotted lines to show the consistency of the results even when wave paths are changed.

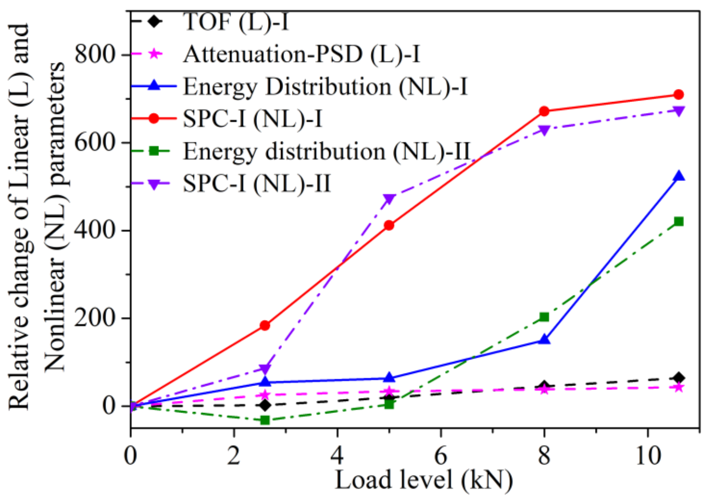

Fig. 2. Comparison of different linear and nonlinear ultrasonic techniques; SPC-I and Energy distribution variations are plotted along two wave propagation paths to examine the consistency of the results. Superiority of SPC-I technique compared to other techniques is obvious from its higher sensitivity to damage, especially at the early stage of loading [5].

3.2 Topological acoustics based geometric phase change (GPC) sensing

As mentioned before for topological acoustics based sensing technique acoustic signals are to be recorded by multiple receiving sensors. Figure 3 shows seven receiving stations marked as

No.1 to 7 on a cracked plate. Different orientations of steel strips in the aluminum plate denoted as X, Y and XY topographies as shown in figure 3 make the plate structure heterogeneous. For X and XY topographies the crack thickness growth remains hidden to the SPC-I technique. However, in figure 4 one can see that the geometric phase difference ($\Delta\phi$) or geometric phase change (GPC) shows significant difference at various frequencies as the thickness of the two cracks shown in figure 3 grows. Therefore, in heterogenous structures having complex topographies, topological acoustics-based GPC technique is recommended for damage growth monitoring.

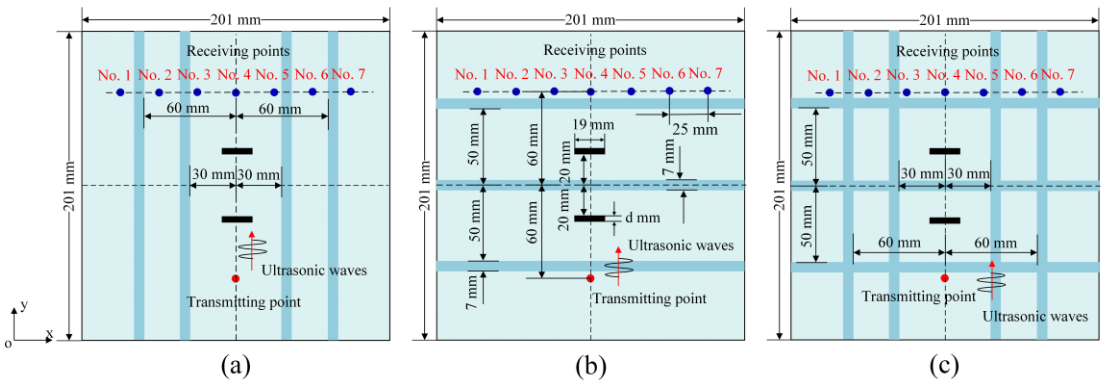

Fig. 3. 2-D views of aluminum plates containing steel strips and two cracks - (a) “X” topography, (b) “Y” topography and (c) “XY” topography [26]

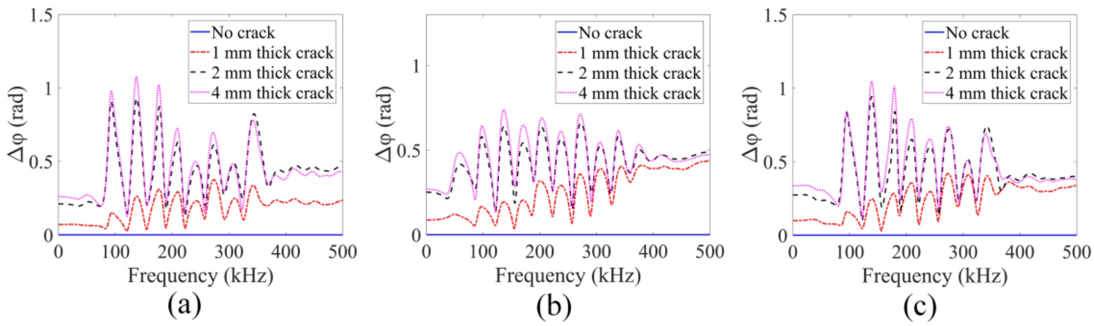

Fig. 4. Geometric phase changes as a function of frequency as the crack thickness increases in plates having (a) “X” topography, (b) “Y” topography and (c) “XY” topography [26]

4. Conclusions

The nonlinear ultrasonic technique SPC-I has been found to be a powerful technique for monitoring various defects (cracks, corrosion, pores etc.) in concrete, metal and fiber reinforced polymer composite materials. In general, SPC-I performs better than other linear and nonlinear ultrasonic techniques. However, in some heterogenous structures the SPC-I technique along with other linear and nonlinear ultrasonic techniques may encounter difficulties in monitoring the damage growth. It is recommended that in those situations the topological acoustics based geometric phase change (GPC) technique be adopted.

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