OPTIMAL SELECTION OF PARAMETERS FOR IMPACT DAMAGE DETECTION IN COMPOSITES BASED ON NONLINEAR VIBRO-ACOUSTICS MODULATIONS

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Abstract

Impact damage detection is one of the most important problems in maintenance of composite structures. Various methods have been developed for the last few decades, including classical non-destructive and structural health monitoring approaches. Recent years have brought significant interest in methods based on nonlinear interactions between damage and ultrasonic waves. The method based on nonlinear vibro-acoustic modulations is one of the examples. Applications of this method to composite structures are still very limited due to two major factors. Firstly, there is very little understanding of the physics behind nonlinear interactions. Secondly, nonlinearities related to intrinsic effects (e.g. material, boundaries, measurement chain) often mask nonlinearities caused by damage. This paper demonstrates how to select frequencies of low-frequency vibration excitation and high-frequency ultrasonic excitation to avoid major difficulties associated with the methods. The results show that optimal selection of these parameters can enhance sensitivity of the method when used for damage detection.

1. Introduction

Composite materials are very often used for structural design due to their properties including low weight, fatigue strength, large damping, corrosion resistance or flexibility to form complex shapes for various applications. They are widely used in many branches of civil engineering (e.g. bridge reinforcements), aerospace industry (e.g. aircrafts elements) process engineering (e.g. tanks, pipes) and many other areas. Despite of all these benefits the noon-resistant of composite materials to impact damage is one of the major concerns related to structural design and maintenance. Impact damage can significantly deteriorate structural integrity due to the fact that most composite structures absorb mechanical energy by elastic deformation or damage mechanisms. In metals plastic deformation is possible and energy absorption mechanisms are different. Low-velocity impacts can introduce various forms of structural damage - e.g. through-thickness buckling, core crushing, de-bonding between core and skins or damage of composite skins such as indentation, delamination or fibre/matrix cracking - leading to severe reduction in strength and integrity of composite structures.

Various methods have been developed for impact damage detection in composite structures, as shown in [1,2]. All these approaches can be divided to active and passive, as discussed in [3]. Recent years have brought interest in various nonlinear ultrasonic methods [4-8]. All these previous studies demonstrate that nonlinearities can result not only from structural damage but also from various intrinsic phenomena (e.g. structural boundaries or measurement chain). It is anticipated that proper selection of excitation parameters - such as frequencies and amplitudes - can enhances the sensitivity of the method to structural damage.The major objective of the paper is to investigate this selection. The paper focuses on the frequency of excitation.

2. Nonlinear acoustics

Many approaches have been developed for damage detection based on nonlinear acoustics. these approaches can be divided into two groups. the first group are the methods based on the so-called classical nonlinear phenomena. the classical theory of elasticity explains nonlinear effect as a results of the nonlinear form of hook's law describing the relationship between stress and strain [9-11] . these nonlinear phenomena are known for many years and used for materials testing applications. classical nonlinearities are manifested in signal response as e.g. higher harmonics or frequency shifts. the second group of methods includes the so-called non-classical phenomena that are based on crack-wave interactions, such as contact acoustic nonlinearity, vibro-acoustic modulations, cross-modulation transfer, energy dissipation via hysteresis or the l-g (luxembourg-gorky) effect [12-15]. these methods are less understood and various theoretical models - that explain non-classical nonlinearities have been proposed, as discussed in [15,16].

The vibro-acoustic modulation technique is a nonlinear damage detection method that has been used in many previous research investigations. In this method the structure is simultaneously excited by low-frequency modal vibration and high frequency acoustic wave. When monitored structures are intact or undamaged, spectra of signal response exhibit only two major frequency components corresponding to the propagating ultrasonic wave and low frequency vibration. When monitored structures are damaged, spectra of response signals contain additionally sidebands around the main ultrasonic component. The number of sidebands and their amplitude depends on the intensity of modulation and strongly relates to damage severity. Classically, for composite-related damage types, modulation of acoustic waves can be explained by closing and opening action of delaminated plies during low-frequency vibrations [17]. This effect is schematically shown in Figure 1.

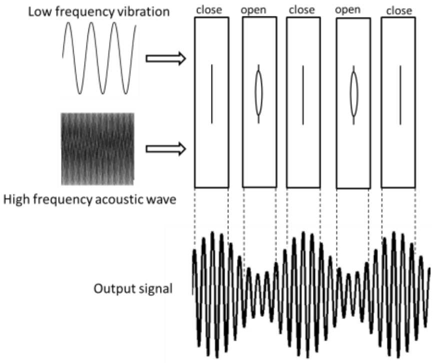

Figure 1. Signal modulation effect observed in delaminated composite plies - the classical explanation.

As a result, signal response spectra contain additional components, i.e. sidebands. Figure 2. gives an example of signal response spectra obtained from a vibro-acoustic modulation test.

Despite the fact that non-linear methods are very sensitive to early-stage damages several problems need to be addressed before any practical implementation. One of the major problems relates to the fact that different nonlinear effects may arise in practice from nonlinear acoustics tests [12,18,19]. It is often very difficult – if not impossible - to separate nonlinear effects related to damage from non-damage-related sources of nonlinearity due to boundary conditions, structural contacts, joints, inherent material nonlinearities or instrumentation measurement chain.

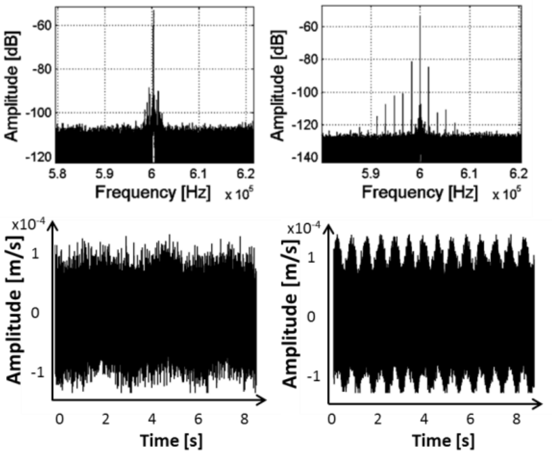

Figure 2. Examples of ultrasonic response power spectra zoomed around high frequency wave and the corresponding time domain signals for non-linear acoustics test: undamaged structure (left) and damaged structure (right).

Another problem associated with nonlinear acoustic methods is related to experimental set-up and procedures. Selection of correct amplitudes, excitation sources as well as their location are very important for these techniques. Selection of excitation frequencies is particularly important. The selection problem of low-frequency excitation has been discussed in [14]. Modal analysis is usually performed before nonlinear acoustic tests to select the best vibration modes for the analysis. The frequency of ultrasonic wave is usually selected arbitrarily.

3. Experimental setup and procedures

The main objective of experimental work performed was to find the optimal frequency for ultrasonic wave in vibro-acoustic modulation tests used for damage detection. Modulation intensity - expressed by the amplitude level of sidebands - was the major criterion behind the optimal selection. This section describes the experimental setup and procedures used in these investigations.

3.1. Test sample – light composite sandwich panel

The test specimen used in this study were light composite sandwich panel, illustrated graphically in Figure 3. The overall dimensions of the panel was 400×120×13.2 mm. The face sheets were made of *Seal Texipreg HS300/ET223* prepreg system, with [0/903/0] ply stacking sequence. The total thickness of the face sheet laminate was 1.6 mm. The core material was a closed cell polyvinyl chloride (PVC) foam *DIAB Divinycell HP60*. The thickness of the foam core was equal to 10 mm. Impact testing was performed to introduce structural damage to the panels. An instrumented drop-weight testing machine was used in these experiments. A hemispherical indenter was used and impact energy was controlled by setting its initial height. The panel was impacted at the central position, as indicated in Figure 3. with the energy of 9.8J.

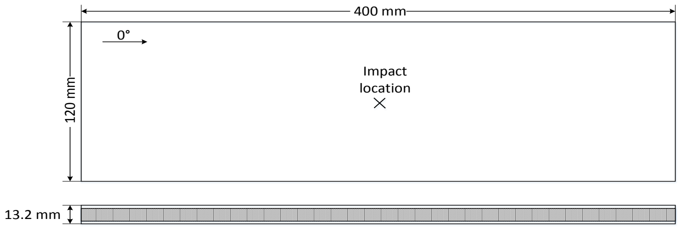

Figure 3. Schematic diagram of Light composite sandwich panel.

3.2. Modal analysis

Experimental modal analysis was performed to estimate structural vibration modes of the panels and select frequencies for low-frequency excitation. The panel was freely suspended using elastic cords to avoid nonlinearities from boundaries. The *PI Ceramics* stack actuator *PL055.30* was used to vibrate the structure. A chirp signal with frequency range from 20 to 2500 Hz was used for excitation. A *Polytec PSV-400* laser vibrometer was used for non-contact measurements of vibration responses. The excitation and response data were used to obtain the Frequency response Function (FRF) shown in Figure 4a. The strongest vibration mode (Figure 4b.) and its 1689 Hz frequency were selected for low-frequency (LF) excitation in vibro-acoustics tests.

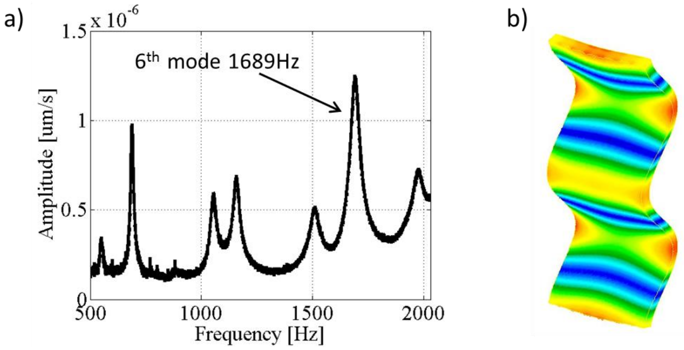

Figure 4. Experimental modal analysis results for the light composite sandwich panel: (a) FRF magnitude; (b) selected 1689 Hz vibration mode.

3.3. Nonlinear acoustic test

The nonlinear vibro-acoustic modulation technique was used for the impact damage detection in the light composite sandwich panels. The tests were performed using the experimental set-up shown in Figure 5. The high-frequency (HF) ultrasonic and the LF vibration excitations were applied simultaneously to the panels. Single-harmonic excitation corresponding to the selected vibration mode (1689 Hz) was used for the LF excitation. The HF excitation utilized a chirp signal with linearly varying frequency range from 20 to 60 kHz within 10 seconds. Excitation signals were generated using an *Agilent 33522A* signal generator and amplified using an *EC Electronics PAQ-G* high-voltage amplifier to the voltage level of 60V. The *PI Ceramics* piezoceramic transducer (diameter - 15 mm, thickness 1 mm) was used for the HF excitation.

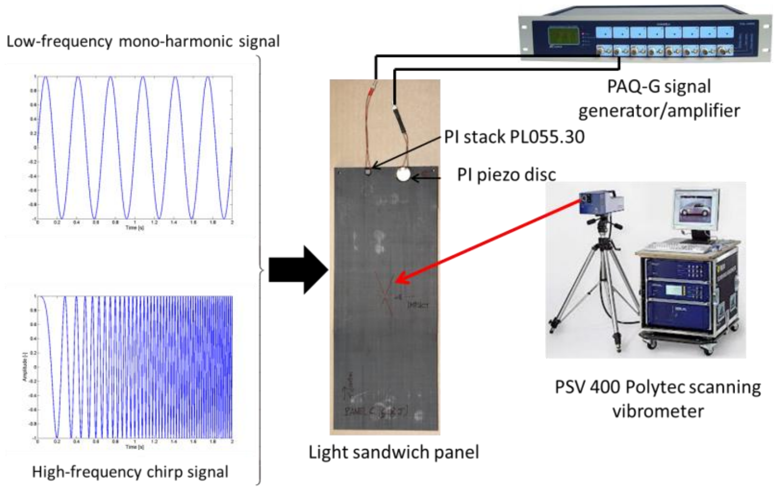

Figure 5. Experimental set-up used for the nonlinear vibro-acoustic tests.

The stack actuator (previously used in experimental modal analysis) was used for the LF excitation Ultrasonic responses were acquired using a *Polytec PSV 400* vibrometer. These responses were taken in the vicinity of damage.

3.4. Signal processing

The application of non-stationary excitation applied requires appropriate signal processing methods. The approach used consist of three main parts. Firstly, signal responses *x(t)* were transformed into the time-frequency domain using the continuous wavelet transform defined as

$$(W_g x)(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) g^*\left(\frac{t-b}{a}\right) dt \tag{1}$$

where b is translation, a is dilatation - also known as a scale parameter - and $g(t)$ is the basic wavelet function. It is well know that the scale parameter a corresponds to frequency according to equation [20]

$$f_a = \frac{f_c}{a \cdot \Delta t} \tag{2}$$

where f_a is the frequency related to a parameter, f_c is the central frequency of the wavelet function used and Δt is the sampling period. The complex Morlet wavelet function was used for calculation. The wavelet transform was calculated for scale parameters ranging from 4 to 10 with the step of 0.25. This range corresponded to the frequency range of the applied chirp excitation.

The second signal processing step involved envelope calculations for all wavelet coefficients related to the set of scale parameter. This operation can be defined as

$$env = \left|(W_g x)(a,b)\right| \tag{3}$$

The time-frequency responses were demodulated around the carrier frequency (corresponding to the relevant a parameter). Finally, spectra for all demodulated signals were estimated to obtain the spectrogram. The entire signal processing procedure used is presented graphically in Figure 6.

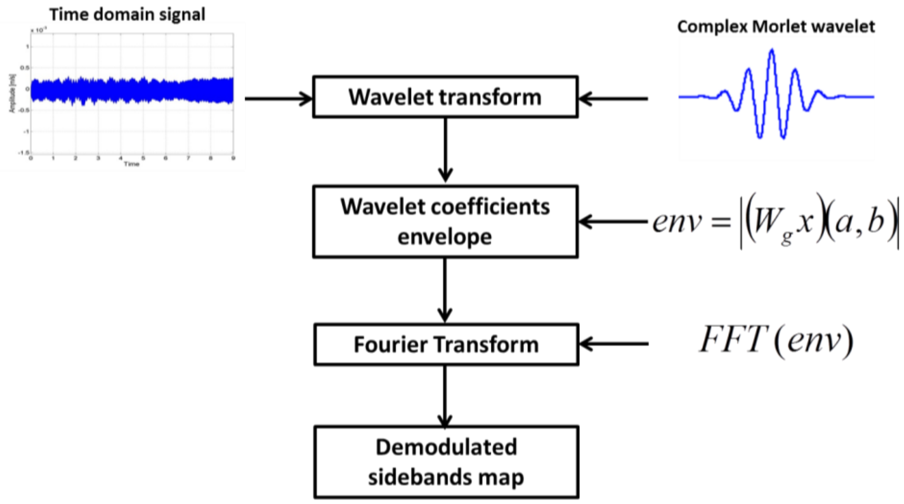

Figure 6. Schematic diagram explaining signal processing used.

4. Results and discussion

Figure 7 gives an example of the spectrogram calculated for one of the acoustical responses acquired in the nonlinear vibro-acoustic modulation test. Harmonics of the fundamental frequency (corresponding to the LF excitation) - and the ultrasonic frequency (corresponding to the HF excitation) and modulation sidebands can be clearly seen in the spectrogram. Since the impacted panel was investigated, the modulation sidebands correspond to the impact damage. These sidebands were not observed when the undamaged panel was tested.

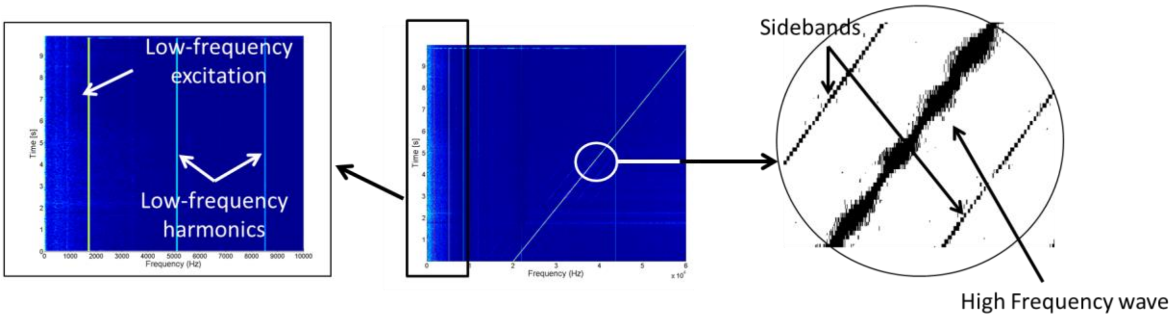

Figure 7. Spectrogram example for ultrasonic response acquired from the nonlinear vibro-acoustic modulation test.

Modulation sidebands were further analysed using cross-sections of the spectrogram, as illustrated in Figure 8. Following this analysis, the amplitude of the modulation sidebands was estimated for all frequencies corresponding to the HF chirp excitation. Figure 9 gives the relevant amplitude vs. HF frequency plot for all analysed sidebands. The maximum amplitude level of the sidebands (and also the largest modulation intensity due to damage) has been achieved when the frequency of the ultrasonic excitation was equal to approximately 36.5kHz. In other words this frequency is the optimal value that should be used for damage detection investigations based on the nonlinear vibro-acoustic tests, for the experimental configuration considered. It is important to note that the actual value of frequency is not important here but the methodology used to obtain the information.

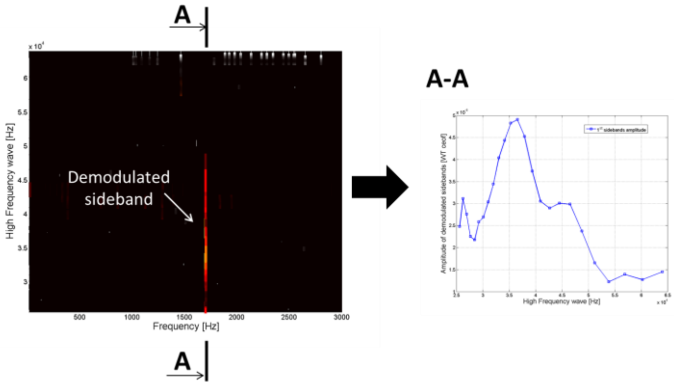

Figure 8. The procedure of sidebands amplitude profiles estimation.

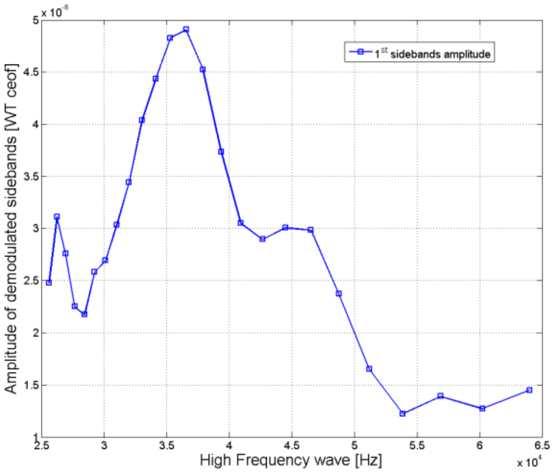

Figure 9. The first sideband amplitude profiles for selected mode shape

5. Conclusions

The algorithm for the selection of ultrasonic HF frequency in nonlinear vibro-acoustics modulation test was presented. The procedure used for this selection is based on broadband, chirp excitation and time-frequency (or time-scale analysis) of modulation sidebands. The results show that the proposed methodology allows one to select the HF frequency optimally, i.e. in such a way that modulation intensities - due to damage - reach the largest possible level for the LF frequency used. The method was used in delaminated light composite sandwich panels that significantly attenuate signal responses.

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