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Vibro-Acoustic Modulation with broadband pump excitation for efficient impact damage detection in composite materials

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Abstract. In the past few decades, the need for efficient and reliable Structural Health Monitoring strategies has led to the development of several approaches for damage detection and characterization purposes. Among them, the Nonlinear Vibro-Acoustic Modulation (VAM) exploits the modulation arising from the interaction of two concurrently applied driving waves, namely the probe and the pump excitations, in the presence of nonlinear scatters such as cracks and defects. Therefore, the VAM provides information on the emergence of internal damage by extracting the nonlinear modulated components of the response of a damaged system. Originally proposed for granular media, the method has shown to be effective in detecting the presence of defects also in metals and composite materials. Nonetheless, its efficacy is highly affected by the excitation frequencies, which are usually chosen among the system resonances. The need for a preliminary modal analysis and, at once, the risk of selecting pump-probe frequency combinations with low sensitivity to damage may make the procedure time-consuming and not fully reliable, preventing the VAM technique from being widely accepted as a robust monitoring tool. To overcome these limitations, a broadband excitation may be used. This study assesses the effectiveness of the VAM technique when a combination of a frequency-swept pump excitation and a mono-harmonic probe wave is applied to drive the sample. Experimental tests were conducted on a composite laminated beam mounted on an electrodynamic shaker and tested in both pristine and damaged conditions. Low-profile surface-bonded piezoceramic transducers were used for both probe excitation and sensing. Barely visible impact damage (BVID) was introduced in the composite beam to examine the potential of the approach for the detection of very small, localized damage. The results show that the use of VAM with a broadband low-frequency excitation may be an effective option for identifying nonlinearities associated with typical damage occurring in composite structures.

1. Introduction

Structural composites are multiphase materials that have been increasingly used in aeronautical, chemical, automotive, and civil engineering, due to their advantageous mechanical properties (e.g., high specific strength and stiffness, excellent resistance to fatigue and corrosion) and flexibility in design. Nonetheless, their susceptibility to impact damage questions the use of composite materials in critical load-bearing applications. For instance, events like bird strikes, hail impacts, and runaway debris during takeoff or landing might trigger the onset of internal damage (e.g., indentation, matrix cracking, delamination, fiber fracture) in aerospace components, severely compromising their structural integrity.

The need to detect and monitor damage at its early-stage resulted in the development of several Non-Destructive Testing (NDT) techniques, which include methods based on visual inspection, acoustic emission, X-rays, ultrasonic waves, thermography, and shearography [1-5]. Despite some attempts to automate inspections, current NDT techniques remain, however, generally time-consuming, labor-intensive, and greatly dependent on the operator's ability.

For these reasons, there is a growing interest in the development and application of Structural Health Monitoring (SHM) techniques [6-9] that may provide a real-time evaluation of the integrity of the structure. Several SHM approaches have been proposed and applied to detect the initiation and growth of damage and defects in structural systems. Guided ultrasonic waves [10, 11] and nonlinear acoustic methods [12] have been widely exploited for damage detection in metal and composite structures due to their ability to inspect large structures with a relatively small number of transducers. Although the pioneering work in the field dates to the 1970s [13, 14], nonlinear acoustic methods, which rely upon the extraction and the analysis of specific features of the system response, have gained increasing interest over the past few decades because of their higher sensitivity to small, localized damage in comparison to linear techniques. Application examples include the Scaling Subtraction Method (SSM) [15, 16], higher harmonic generation [17, 18], resonance spectra [19], frequency mixing [20], modulation analysis [21-25]. In particular, the damage detection approach based on the *Vibro-Acoustic Modulation* (VAM), also referred to as *Nonlinear Elastic Wave Spectroscopy* (NEWS) [20] exploits the vibro-acoustic interaction between two impinging waves (namely, the pump and the probe waves) concurrently applied to the inspected system. The interaction of the two waves at a damaged region generates nonlinear modulating effects, which may be observed as additional frequency components (sidebands) in the spectral response of the system and provide an indication of the presence of damage in the material. Introduced in the 1990s [26, 27] for the detection of contact-type defects (e.g., cracks), VAM was subsequently applied to a variety of materials and structural defects, such as fatigued steel beams [21], fatigued aluminum beams and plates [28, 29], loose bolt connections [30], and kissing bonds [31], showing high sensitivity to damage initiation and advantageous low-cost hardware implementation [24, 32].

The effectiveness of VAM in detecting impact-induced damage in composite structures was first assessed by Meo and Zumpano [33], who analyzed the nonlinear features of the vibro-acoustic response of a sandwich composite previously impacted by a sharp object. Later, Aymerich and Staszewski [34] applied the VAM approach to monitor the progression of internal damage in a multidirectional composite plate subjected to multiple low-velocity impacts and highlighted the role of the boundary conditions on the performance of the method. Klepka et al. [23] investigated the effect of the pump and probe frequency, usually chosen among the system resonances, on the modulation intensity. The study shows that higher nonlinear features effects are achieved by combining a probe frequency matching the local damage resonance with a pump frequency that excites the damage interfaces in the out-of-plane direction. The need for a preliminary modal analysis to determine the resonance frequencies of the system and the lack of an established procedure of general validity to select the most suitable excitation frequencies are the main current limitations of the VAM approach. In order to circumvent these limitations, broadband excitations, covering a wide range of probe or pump frequencies in a single test, may be used.

Many attempts to apply a wide-band probe signal to identify the occurrence of internal damage have already been reported in the literature [29, 35-37]. In contrast, only a minor effort has been dedicated to investigating the use of a broadband pump excitation. Donskoy et al. [38] examined the response of fatigued steel samples subjected to an impulsive pump excitation consisting of the superposition of multiple bending modes. They showed that the perturbation introduced in the cracked region and, thus, the modulation intensity, greatly depends on the applied vibration mode. More recently, the VAM technique was used by the authors with a multi-modal pump excitation to detect barely visible damage in a composite beam [39]. The method was found to be effective, though affected by the position of the sensor with respect to the bending shape of the selected pump frequency. The response of the system was acquired using single-axis accelerometers, which measure along the direction perpendicular to the mounting surface and thus along the direction of the bending deflections of the examined beam. Low-profile PZT sensors are however much more commonly used than accelerometers in SHM applications, because of their low cost, small size, and good frequency response. Moreover, they do not require dedicated signal conditioners or amplifiers. These sensors exhibit their highest sensitivity to in-plane deformations, in contrast to the transverse sensitivity of accelerometers. In this context, the present study aims to assess the effectiveness of a VAM testing approach based on broadband pump excitation for impact damage detection when low-profile PZT transducers bonded to the surface are used to sense the response of the beam. The VAM tests were conducted on a composite beam simultaneously vibrated through a shaker and a surface bonded PZT actuator. Low-profile surface-bonded piezoceramic transducers were used for sensing. The beam was tested first in the pristine and then in a damaged condition, obtained by subjecting the beam to a low-velocity impact, to assess the potential of the VAM method for detecting barely visible impact damage in composite structures.

2. Nonlinear Vibro-Acoustic Modulation

Nonlinear Vibro-Acoustic Modulation (VAM) techniques rely upon the simultaneous application of two excitation signals of distinct frequency and amplitude: a low-frequency, high-amplitude wave (*pump signal*) that perturbs the material at the damaged region and a low-amplitude, high-frequency wave (*probe signal*) that captures the nonlinearities in the material behavior generated by the pump excitation. Under the hypothesis of perfect linearity, the response of the material varies proportionally to the applied excitation and the superposition principle holds. Therefore, since the input provided in a VAM test consists of two harmonic excitations, the response of the inspected sample $u\ (t)$ can be written as a linear combination of the two responses $u_{LF}\ (t)$ and $u_{HF}\ (t)$:

$$u\ (t) = u_{LF}\ (t) + u_{HF}\ (t) = U_{LF} \sin(\omega_{LF}\, t) + U_{HF} \sin(\omega_{HF}\, t) \tag{1}$$

Here U_{LF} and U_{HF} respectively indicate the amplitude of the system response at the pump (ω_{LF}) and the probe (ω_{HF}) frequency. Therefore, the spectrum of the response of a linear undamaged material exhibits only the two frequency components corresponding to the pump and the probe excitation signals (figure 1).

Conversely, the presence of internal damage (e.g., cracks, delamination, cracks, and kissing bonds) perturbates the propagation of elastic waves and triggers the emergence of modulation effects. Although the mechanisms underlying the modulation of an acoustic wave are still not completely understood, it is widely accepted that they rely upon the nonlinear contact dynamic. Phenomena occurring within the damaged area, such as contact, decohesion, clapping, and friction, cause the material to behave nonlinearly against the applied inputs, which lead to the generation of additional spectral components. Thus, the time-domain response of a nonlinear system can be expressed as [31]:

$$u\ (t) = U_{LF} \sin(\omega_{LF}\ t) + U_{HF} \sin(\omega_{HF}\ t) + \sum_i H_{LF,i} \sin(i\ \omega_{LF}\ t) + \sum_j H_{HF,j} \sin(j\ \omega_{HF}\ t) + \sum_i \sum_j U_{SB,i\pm j}\ \sin(i\ \omega_{LF}\ t \pm j\ \omega_{HF}\ t) \tag{2}$$

where $H_{LF,i}$ and $H_{HF,i}$ respectively represent the amplitude of the higher harmonics of the pump and probe signal, while $U_{SB,i\pm j}$ represent the amplitudes of multiple mixed frequency components, which are generally referred to as modulation sidebands (figure 1). The number of sidebands and their amplitude depends on the modulation intensity, which is related to damage severity. It is, however, worth remarking that non-damage-related nonlinear effects, such as those arising from boundaries, inherent material nonlinearities, or the adopted instrumentation, might trigger the emergence of similar nonlinear effects. Thus, a certain number of modulation sidebands will be generally present even in the spectrum of an intact structure, regardless of the employed equipment or the applied approach [21].

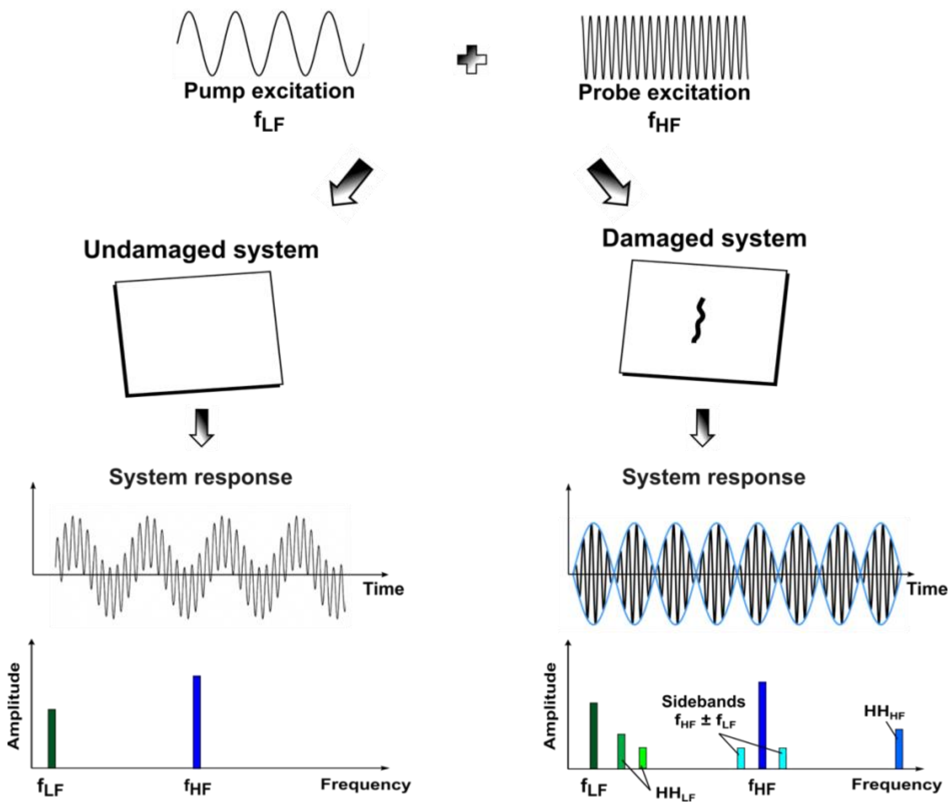

Figure 1. Schematic representation of the Nonlinear Vibro-Acoustic Modulation (VAM).

3. Experimental setup and preliminary analysis

Experimental tests were carried out on a laminated composite beam manufactured from *Seal Texipreg ® HS160/REM* carbon/epoxy unidirectional prepreg plies (0.17 mm nominal thickness). The sample was cut in the shape of a 530 mm × 59 mm x 2 mm beam (figure 2) from a panel laminated with a $[0/90]_{3s}$ stacking sequence and cured in autoclave at a maximum temperature of 160 °C and a pressure of 6 bar. Before testing, the specimen was ultrasonically C-scanned to assess the quality of the laminate and to exclude the presence of possible manufacturing defects.

The sample was mounted on a *Bruel and Kjaer 480*9 electrodynamic shaker using a threaded aluminum stud glued at its bottom surface. Three *PI Ceramic PIC 15*1 low-profile piezoceramic transducers (10 mm diameter, 1 mm thickness), positioned as shown in figure 2, were surface bonded using a two-component epoxy adhesive and wired using additionally welded connectors. In particular, the piezoceramic transducer at location A1 was used as high-frequency actuator, while those at locations S1 and S2 were employed to sense the system response. During the tests, the shaker was driven by a signal provided by a *TTI-TGA1241* function generator and amplified through a *Bruel & Kjaer 2706* power amplifier, while a *TTI TG5011* function generator in association with a *FLC F20A* amplifier was used to control the PZT transducer bonded at location A1. The response of the sample was acquired at the two sensors (S1 and S2 in figure 2) using a 14-bit, 100 MSa/s, PC-controlled oscilloscope (*Cleverscope CS328A*). The instrumentation used to carry out the experimental investigations is shown in figure 3.

An instrumented drop-weight testing machine, whose 2.34 kg impactor was equipped with a hemispherical indenter of 12.5 mm diameter, was used to impact the sample with a 1.9 J energy. Non-destructive penetrant-enhanced X-ray images were taken to assess the nature and extent of internal damage. As illustrated in figure 4, the induced damage is mainly a combination of matrix cracks and delaminations, with a projected damage area of about 40 mm^2. Short fiber fracture paths can be also observed at the boundary of the indentation area.

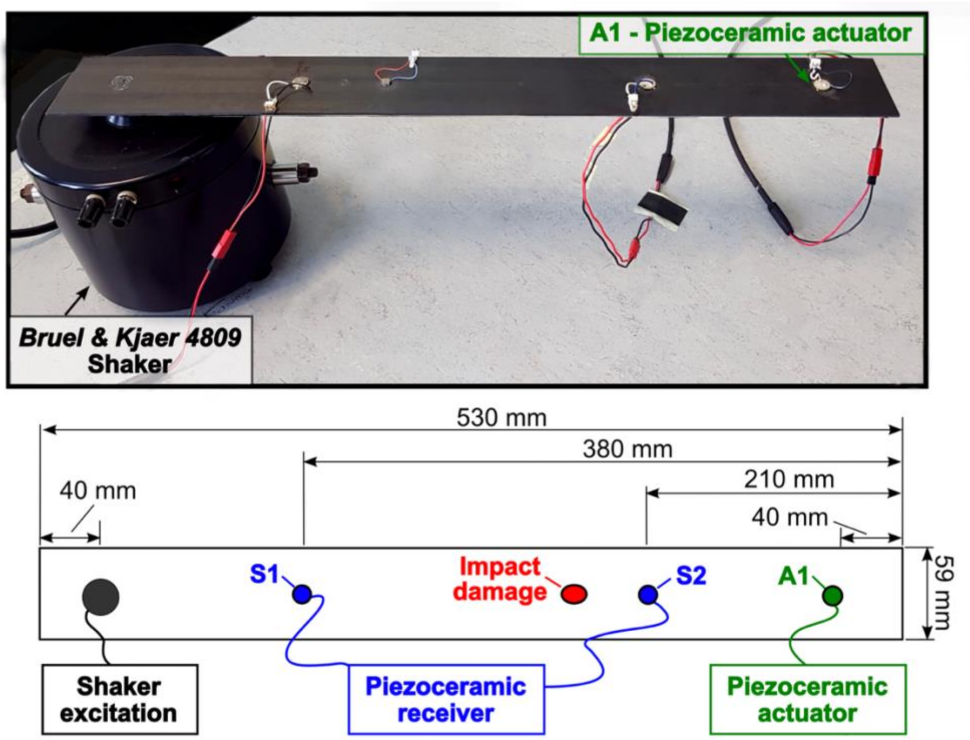

Figure 2. Schematic representation of the adopted experimental setup.

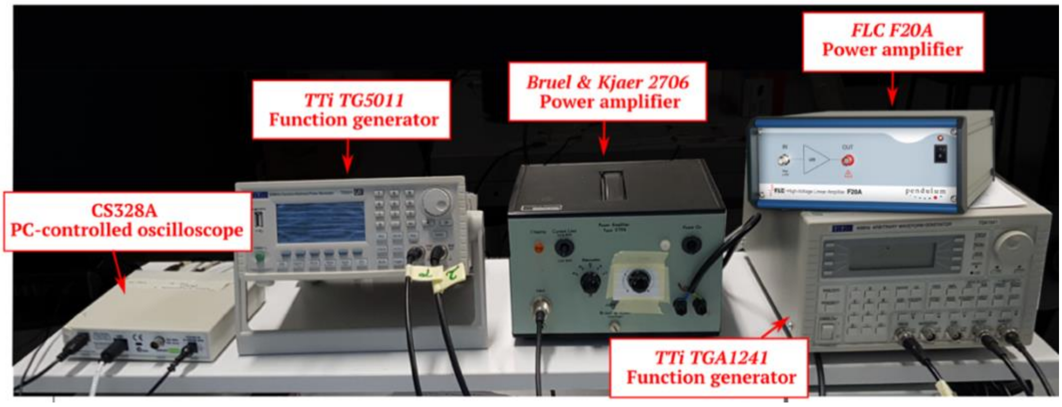

Figure 3. Instrumentation used for the experiments.

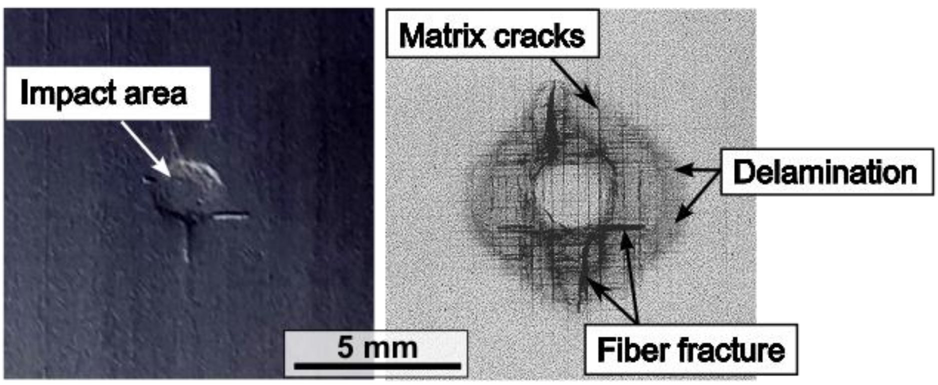

Figure 4. Impacted region (left) and X-ray image (right) of the internal damage induced by a low-velocity impact of 1.9 J energy.

To preliminarily characterize the modal response of the system, the composite sample was excited through a sweep sine signal ranging from 1 Hz to 1200 Hz in 4 s. The response of the inspected sample was acquired at locations S1 and S2. In order to increase the signal-to-noise ratio, forty data sets were recorded and post-processed in *Matlab* to calculate the average power spectrum. The averaged FFT amplitude, presented in figures 5 and 6, shows the first eigenfrequencies of the plate. Two frequency ranges around the resonance frequencies of 316 Hz and 510 Hz were chosen to explore the effectiveness of a broadband pump excitation in the VAM techique. A numerical modal analysis performed in *Abaqus* revealed that the mode shapes associated with these two selected frequencies are characterized by out-of-plane bending (figure 7).

A similar procedure was applied to select the probe frequency value. In this case, a linear sweep sine signal ranging from 5 to 40 kHz in 10 s was fed into the low-profile piezoceramic transducer bonded at location A1. The vibration patterns were again recorded at sensor locations S1 and S2 and then processed to obtain the corresponding spectra (figures 8 and 9). The 21070 Hz resonance frequency, characterized by a high relative amplitude at both S1 and S2 locations, was chosen for the subsequent VAM experiments.

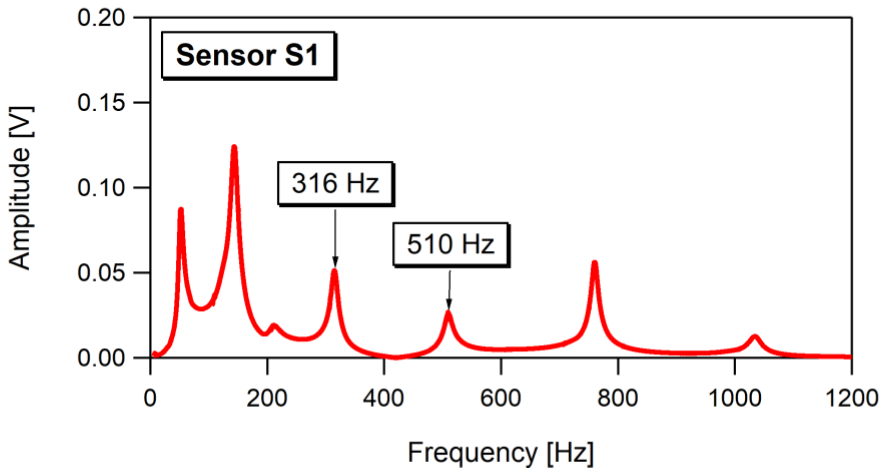

Figure 5. Power spectrum (low-frequency range) taken at sensor location S1.

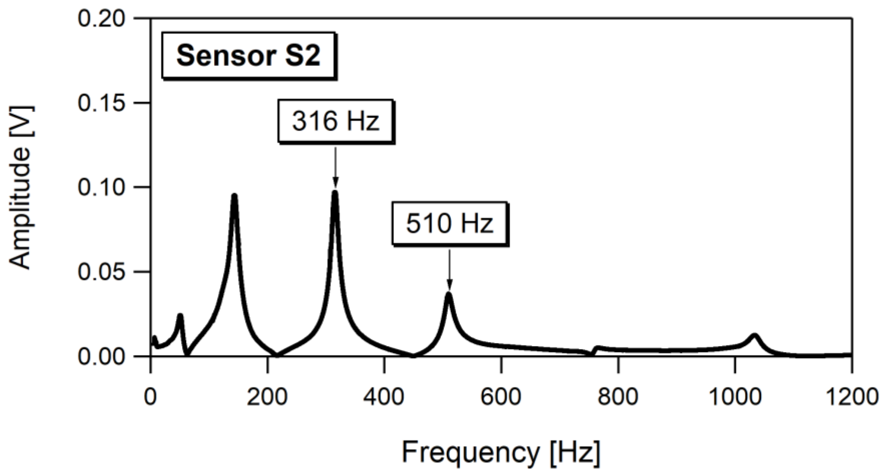

Figure 6. Power spectrum (low-frequency range) taken at sensor location S2.

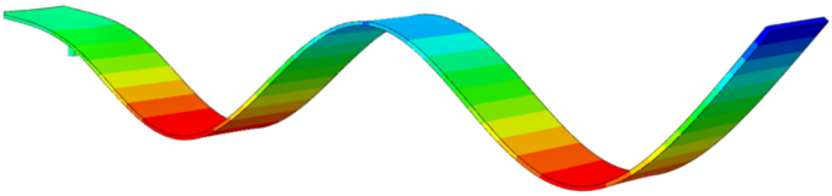

Figure 7. Numerically predicted mode shapes corresponding to the selected resonance frequencies.

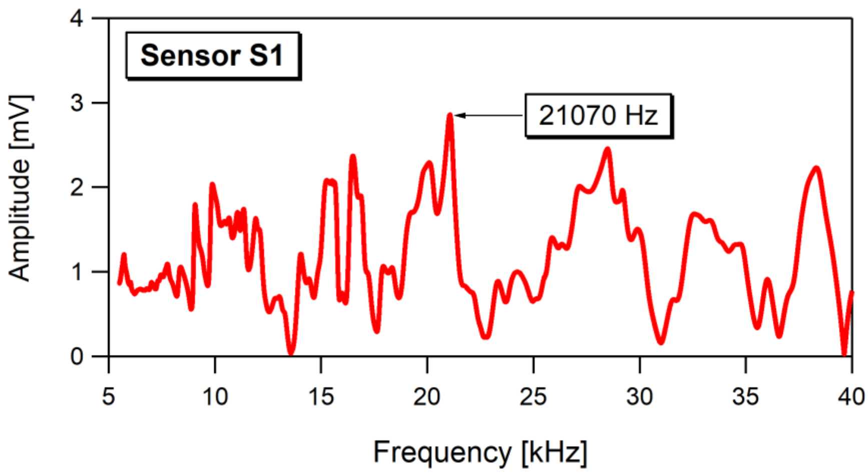

Figure 8. Power spectrum (high-frequency range) taken at sensor location S1.

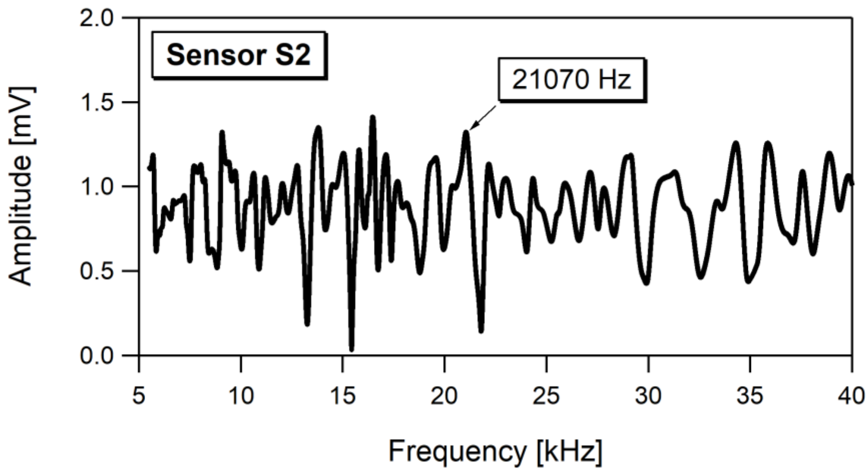

Figure 9. Power spectrum (high-frequency range) taken at sensor location S2.

4. Nonlinear Vibro-Acoustic Modulation tests and results

In the vibro-acoustic tests, the laminated composite beam was vibrated through a broadband pump excitation and a simultaneous mono-harmonic probe wave. The pump signals consisted of linear sine sweeps that included the two selected resonance frequencies (i.e., 316 Hz and 510 Hz). The frequency of the pump wave was initially swept across the range 240÷360 Hz in 10 s and, subsequently, over the range 440÷560 Hz in 10 s. Three pump excitation levels, namely 50 mVpp, 250 mVpp, and 1 Vpp, were considered for testing. Concurrently, a 21070 Hz pure-tone harmonic signal (probe excitation) was fed into the piezoceramic transducer at location A1. The system response was sensed at locations S1 and S2, and recorded at a sampling rate of 400 kSamples/s. The acquired data were averaged over ten data sets and post-processed by a Short-Time Fourier Transform (STFT) algorithm. To this purpose, 69 sub-windows with 30% overlapping were used.

Figures 10-13 show the STFT spectrograms of the acoustic response of the inspected sample over the two considered frequency ranges and for the three considered pump excitation levels (i.e., 50 mVpp, 250 mVpp, and 1 Vpp). Figures 10 and 11 refer to the signals acquired at sensor location S1, while figures 12 and 13 correspond to the response sensed at location S2. The spectrograms provide information on the amplitude (represented by the grey intensity) of the frequency content of the system response (horizontal axis) as it varies against the instantaneous pump frequency (vertical axis). In order to assess the emergence of modulation sidebands, the spectrograms were zoomed around the spectral line corresponding to the probe frequency (i.e., 21070 Hz). Examples of the averaged power spectra corresponding to a specific pump frequency value are shown below the associated spectrograms.

As expected, the higher amplitude contained in the spectrograms corresponds to the frequency of the probe excitation, while the modulation sidebands are visible as thin straight lines with a distance from the probe frequency varying linearly with the instantaneous frequency content of the swept pump signal. The comparison of the spectrograms obtained for the different sensor positions and the three levels of pump excitation shows that the intensity of the modulation sidebands depends on the pump excitation energy and frequency, as evidenced by other previous studies [21, 28]. For instance, for the pump excitation amplitude of 250 mVpp and the sensor location S2, no sidebands appear for the range 240-360 Hz (see figure 12b), while they are clearly visible in the damaged condition for the range 440-560 Hz (figure 13b).

The spectrograms also show that the modulation intensity is affected by the sensor position. For example, for the pump amplitude of 250 mVpp and the range 240-360 Hz, sidebands do not emerge when the sensor is in position S2 (figure 12b), while they are evident for sensor location S1 (figure 10b). The effect of the position of the sensor on the modulation intensity was investigated in other studies and was seen to depend on the distance of the sensor location from the nodal points of the deformed beam at the excitation frequency [39].

Examining, in particular, the response of the beam acquired at the position S1 we may see that when the amplitude of the provided pump input is increased from 50 mVpp to 250 mVpp, a clear pattern of modulation sidebands emerges in the spectrogram of the damaged sample (figure 10 and figure 11). These sidebands exhibit higher amplitudes in the proximity of the resonance frequency, thus showing the influence of the interrogating pumping frequency on the modulation intensity and, in turn, on the detection capabilities of the Vibro-Acoustic Modulation.

The comparison of the spectrograms acquired at 50 mVpp and 250 mVpp in damaged conditions highlights the importance of the excitation level on the VAM sensitivity and shows that enough energy is required to activate and detect the material nonlinearities. On the other hand, the spectrogram acquired at 1 Vpp (see figures 10c and 11c) indicate that the method's effectiveness might be compromised when comparatively too high pump excitation levels are adopted. As a matter of fact, these spectrograms reveal a significant increase in the background noise, as indicated by the change in the grey intensity, which makes it almost impossible to distinguish the presence of modulation sidebands. This evidence might be linked to the intrinsic characteristics of the adopted equipment. For example, when powered, the electrodynamic shaker generates an electromagnetic field that varies its intensity proportionally to the amplitude of the applied input. The induced electromagnetic interference reduces the signal-to-noise ratio of the signal received from the PZT sensors, compromising the VAM performance.

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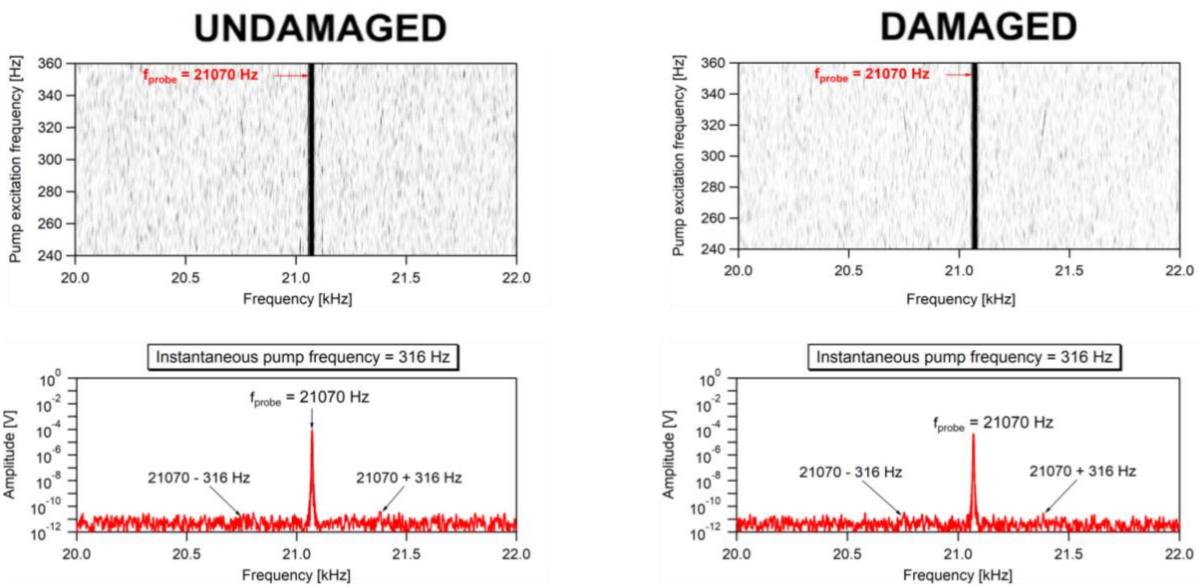
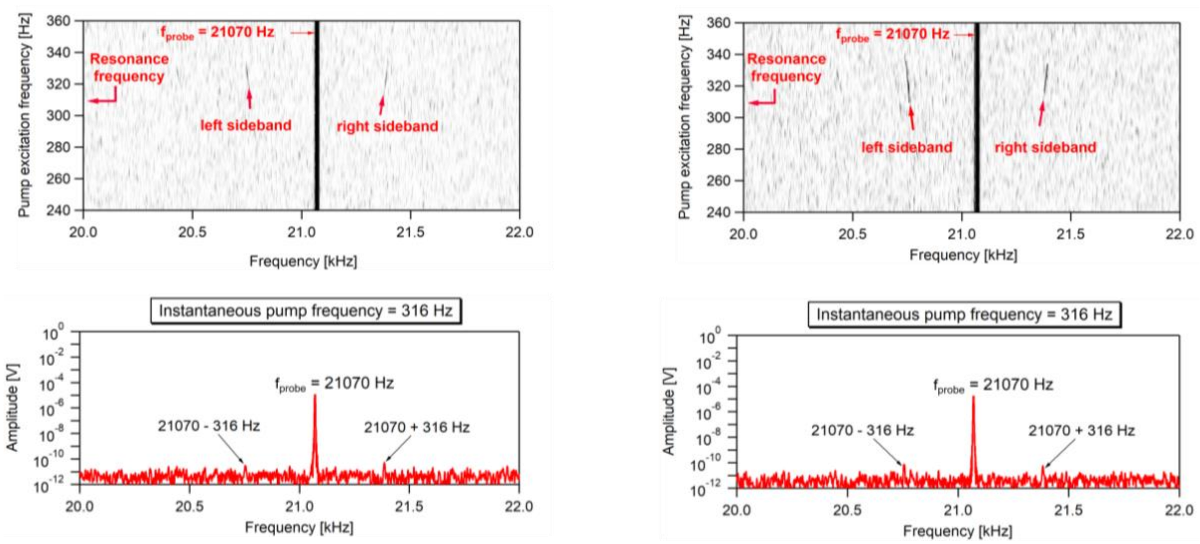
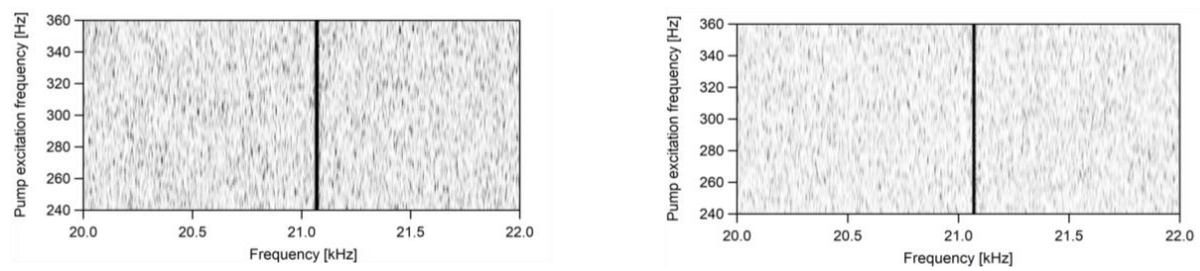


(a) Excitation amplitude 50 mVpp

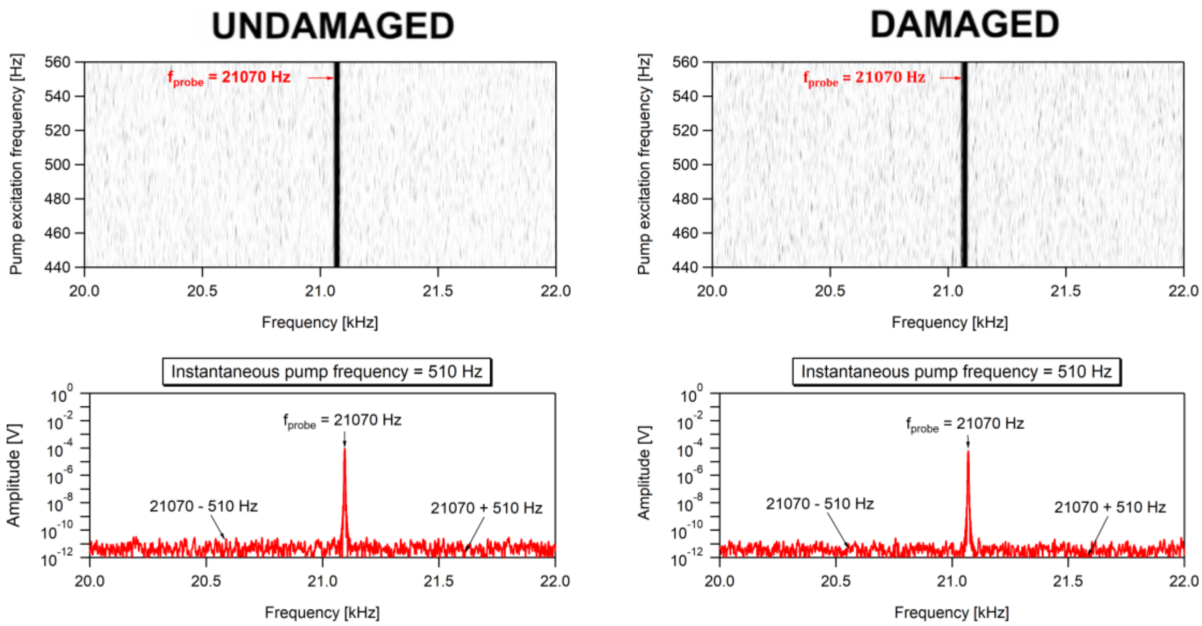


(b) Excitation amplitude 250 mVpp

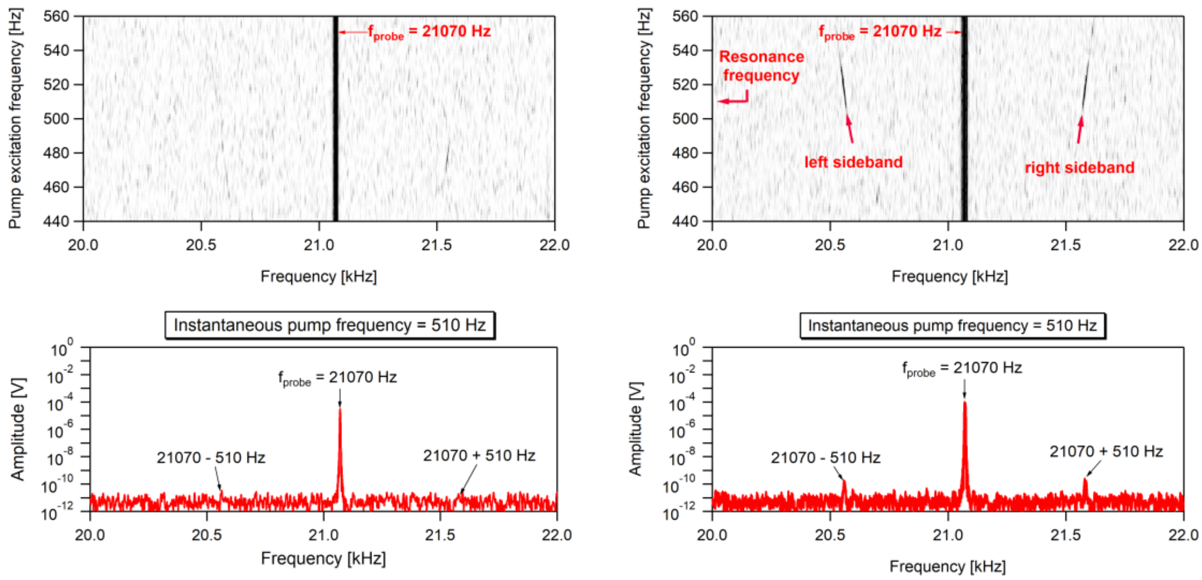


(c) Excitation amplitude 1Vpp

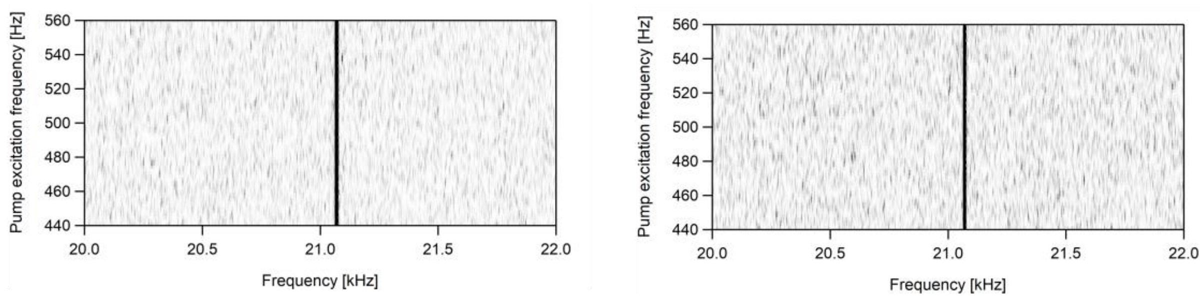
Figure 10. Spectrograms of the beam response to a swept pump excitation ranging from 240 Hz to 360 Hz at sensor location S1 in pristine (left) and damaged (right) conditions. The data were acquired at a pump excitation amplitude of 50 mVpp (a), 250 mVpp (b), 1Vpp (c).



(a) Excitation amplitude 50 mVpp

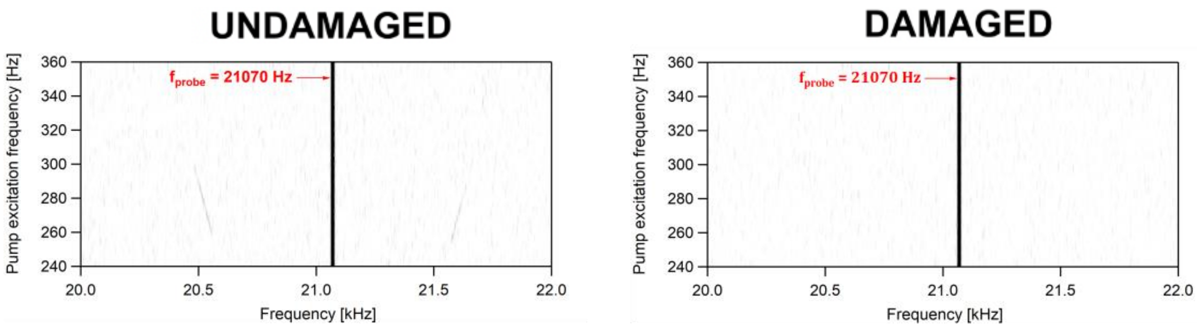


(b) Excitation amplitude 250 mVpp

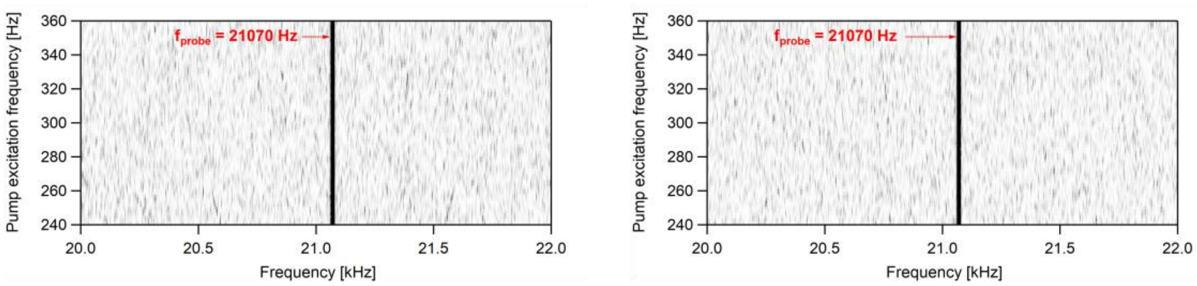


(c) Excitation amplitude 1 Vpp

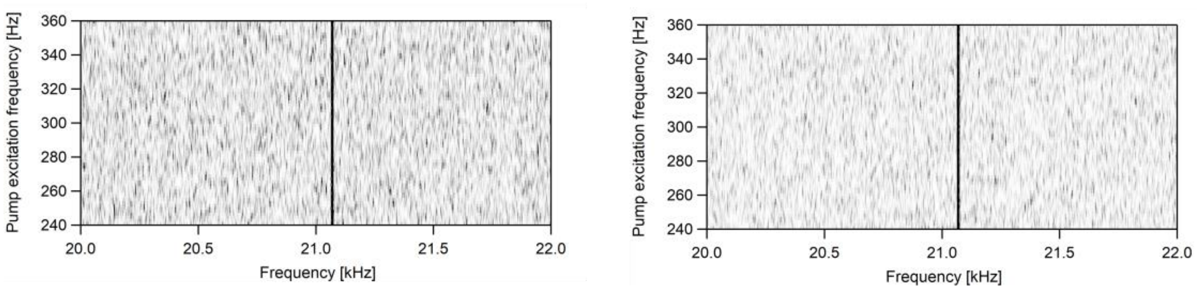
Figure 11. Spectrograms of the beam response to a swept pump excitation ranging from 440 Hz to 560 Hz at sensor location S1 in pristine (left) and damaged (right) conditions. The data were acquired at a pump excitation amplitude of 50 mVpp (a), 250 mVpp (b), 1Vpp (c).



(a) Excitation amplitude 50 mVpp

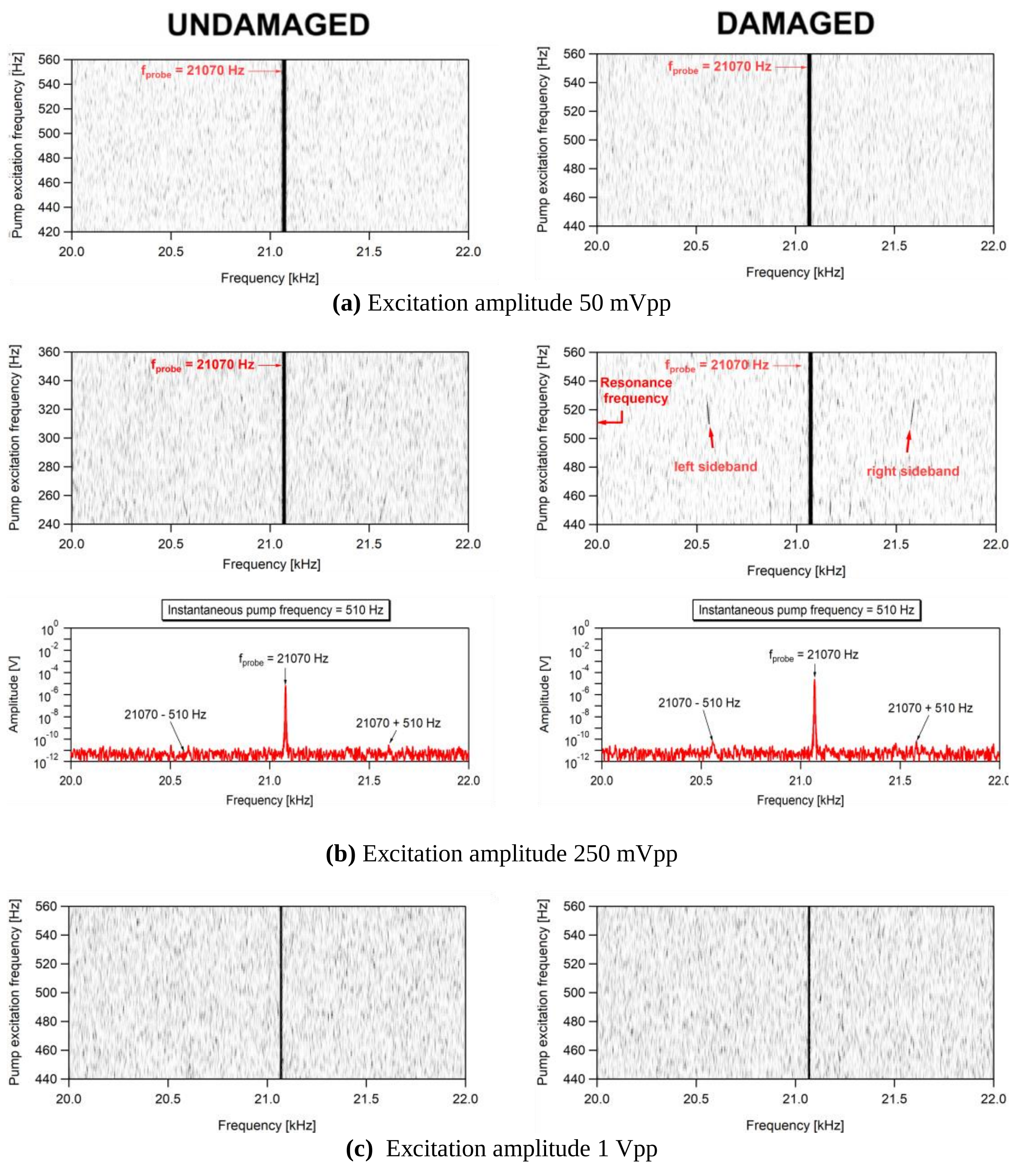


(b) Excitation amplitude 250 mVpp



(c) Excitation amplitude 1 Vpp

Figure 12. Spectrograms of the beam response to a swept pump excitation ranging from 240 Hz to 360 Hz at sensor location S2 in pristine (left) and damaged (right) conditions. The data were acquired at a pump excitation amplitude of 50 mVpp (a), 250 mVpp (b), 1Vpp (c).



(a) Excitation amplitude 50 mVpp

(b) Excitation amplitude 250 mVpp

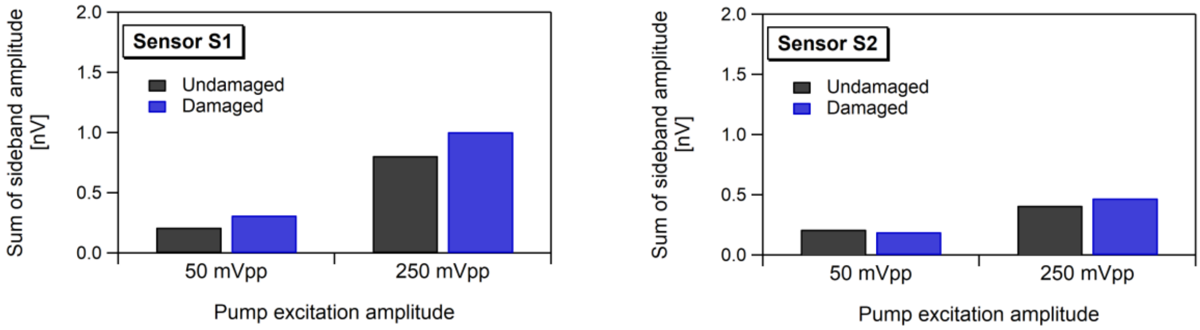
(c) Excitation amplitude 1 Vpp

Figure 13. Spectrograms of the beam response to a swept pump excitation ranging from 440 Hz to 560 Hz at sensor location S2 in pristine (left) and damaged (right) conditions. The data were acquired at a pump excitation amplitude of 50 mVpp (a), 250 mVpp (b), 1Vpp (c).

In order to provide a quantitative indication of the effectiveness of the sweep-based VAM approach to the presence of Barely Visible Impact Damage (BVID) in composite samples, the values of the magnitude of the modulation sidebands were calculated from the STFT spectrograms for different levels of the pump signal. For this purpose, the two pump frequency ranges were divided into twelve sub-ranges with a frequency width of about 12 Hz. The average magnitudes of the sidebands within each sub-range were extracted, summed, and then plotted as a function of the pump excitation amplitude.

The graphs in figure 14 show, for each sensor location, the cumulative amplitude of the modulation sidebands over the two considered sweep frequency ranges (240÷360 Hz and 440÷460 Hz), which provides a global indication of the method's ability to detect changes in the nonlinear content of the system response. Because of the significant increase of the background noise retrieved at 1 Vpp, the graphs show only the results associated with 50 mVpp and 250 mVpp amplitude levels.

The results obtained for data acquired at position S1 (figure 14a) show modulation intensities always higher for the damaged beam than for the pristine beam, indicating the general ability of the Vibro-Acoustic Modulation to detect the presence of impact-induced damage. It is also seen that the increase in the sideband amplitude generated by the damage is more marked for the higher pump excitation level, confirming the importance of perturbing with a sufficient pump energy the linearities to be sensed by the probing signal. On the other hand, the data acquired by the sensor in S2 (figure 14b) show quite similar values for the sideband amplitudes recorded for the undamaged and damaged conditions, thus revealing the strong influence of sensor position on the performance of the method.

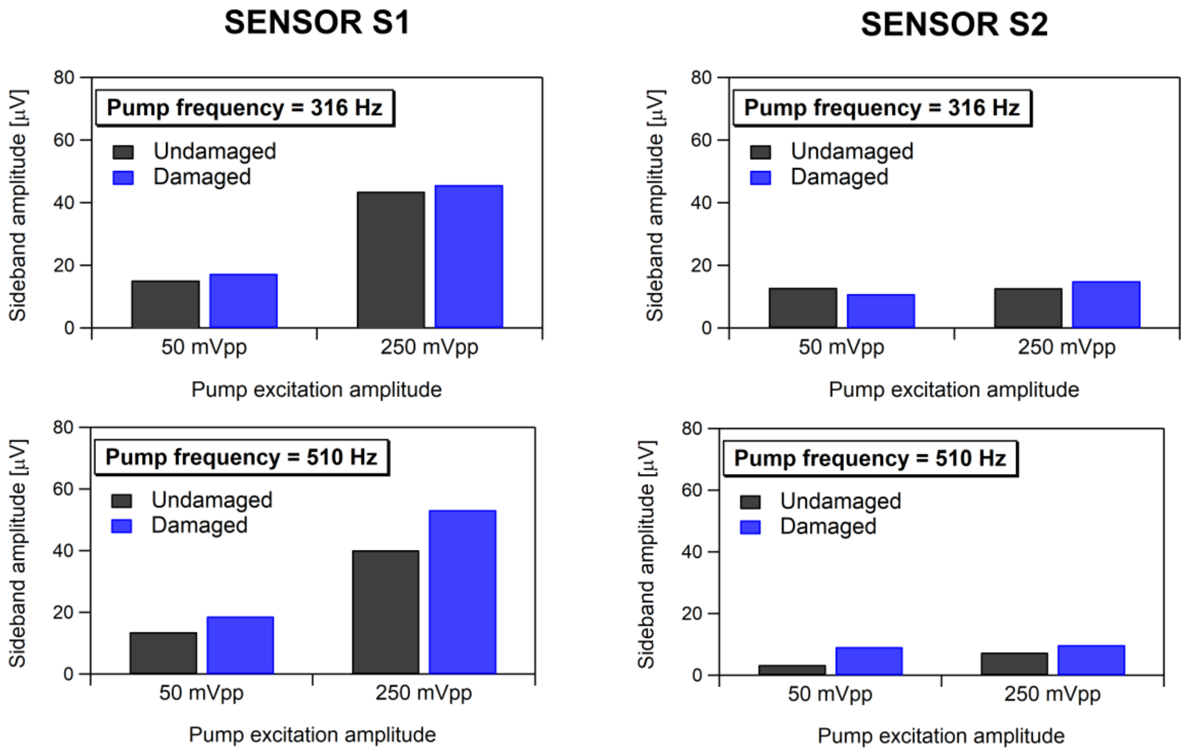


(a) (b)

Figure 14. Cumulative sum of the average sideband amplitudes recorded in both the undamaged and damaged conditions at sensor S1 (a) and sensor S2 (b), for two excitation levels. Data are obtained by vibrating the inspected sample through a combination of a swept pump excitation and a pure-tone probe signal.

As a final attempt to explore the quality of the indications provided by the sweep-based VAM approach, a series of conventional vibro-acoustic tests was carried out exciting the inspected sample with a combination of two pure-tone driving signals. The resonance frequencies of 316 Hz and 510 Hz were chosen for the pump excitation, while the 21070 Hz frequency was selected for the probe excitation. In correspondence to each of the considered testing scenarios, twenty data sets were recorded and post-processed to determine their averaged Fast Fourier Transform. The amplitude of the first pair of modulation sideband was extracted and, subsequently, plotted against the pump excitation level (figure 15).

The graphs shown in figure 15 reveal general trends and provide indications like those obtained for the sweep pump excitation. In particular, the data of figure 15 show not only that the performance of the technique strongly depends on the position of the sensor and on the amplitude of the pump excitation, but also that the choice of a suitable pump frequency is required for a reliable detection of the introduced damage. These results clearly suggest the adoption of a sweep multi-mode pump excitation to increase the effectiveness and robustness of VAM-based approaches to detect impact damage at its early stage in composite laminates.



(a) (b)

Figure 15. Sideband amplitudes recorded in undamaged and damaged conditions at the sensor location S1 (a) and sensor S2 (b) for two pump excitation levels. The data plotted in these graphs were obtained by vibrating the inspected sample through a combination of two pure-tone signals.

Conclusions

The present study provides a further analysis of the potential of a sweep-based VAM approach to identify the occurrence of barely visible impact damage in composite materials. For this purpose, a laminated composite beam, tested in pristine and damaged conditions, was vibrated through a combination of a frequency-swept pump signal and a mono-harmonic probe wave. The response of the system to the excitations were acquired by low-profile PZT sensors. The obtained results allow us to draw the following insights:

- The application of a broadband swept signal is a promising option to detect the presence of barely visible impact damage in composite laminated beam.
- The adopted approach has strong potential to improve the reliability and robustness of the VAM technique. In particular, the use of a broadband pump excitation: (1) avoids the need of a preliminary modal analysis to identify the system resonances; (2) reduces the risk of selecting pump-probe frequency combinations with low sensitivity to damage; (3) allows to excite effective resonance frequencies even when they shift because of damage or of possible changes of environmental or boundary conditions.
- The selection of the excitation level has a critical influence on both the effectiveness and the sensitivity to damage of the VAM technique. The experimental evidence shows that small internal damage may remain undetected when the energy provided to the sample is not sufficient to activate the damage induced nonlinearities.

Nonetheless, further investigations are required to broaden the scope of application and verify its performance when different types and severity of internal damage, as well as boundary and environmental conditions, are considered.

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