

PAPER • OPEN ACCESS

## Damage Detection in Composite Materials by Flexural Dynamic Excitation and Accelerometer-Based Acquisition

To cite this article: G Loi *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1214** 012007

View the [article online](#) for updates and enhancements.

You may also like

- [Study of micro-crack localization based on vibro-acoustic modulation](#)  
Caini Xiao, Huifeng Zheng, Liuchen Hu et al.
- [Influence of Voluntary Associations of Municipalities on the Territory Development](#)  
Gabriela Kocourkova, Dagmar Hrabincova, Alena Ticha et al.
- [Application of humic acid and Vesicular Arbuscular Mycorrhiza \(VAM\) for growth and production of soybean](#)  
A H Bahrun, A Mollah and N H Khotimah



The Electrochemical Society  
Advancing solid state & electrochemical science & technology

242nd ECS Meeting

Oct 9 – 13, 2022 • Atlanta, GA, US

Abstract submission deadline: **April 8, 2022**

Connect. Engage. Champion. Empower. Accelerate.

**MOVE SCIENCE FORWARD**



Submit your abstract



# Damage Detection in Composite Materials by Flexural Dynamic Excitation and Accelerometer-Based Acquisition

G Loi<sup>1</sup>, N Uras<sup>2</sup>, M C Porcu<sup>2</sup> and F Aymerich<sup>1</sup>

<sup>1</sup> Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Piazza d'Armi, 09123 Cagliari, Italy

<sup>2</sup> Department of Civil-Environmental Engineering and Architecture, University of Cagliari, Piazza d'Armi, 09123 Cagliari, Italy

*E-mail address:* gabriela.loi@unica.it

**Abstract.** Composite materials provide many advantages over more conventional materials. However, their susceptibility to impact damage can question their use in critical load-bearing structures, and efficient methods are needed for early damage detection. To this purpose, the nonlinear vibro-acoustic modulation (VAM) technique applies a low-frequency pump excitation and a high-frequency probe excitation to exploit the onset of harmonic components around the probe frequency of the damaged structural response. The VAM technique has been widely studied on structures instrumented with piezoceramic transducers used for both actuation and sensing, but few attempts have been made to use equipment typical of modal testing, such as shakers and accelerometers. In this study, the VAM technique is applied to a composite laminate beam by employing an electro-dynamic shaker to generate low-frequency flexural excitation, a low-profile piezoceramic transducer to introduce the probe wave, and a micro-accelerometer to sense the structural response. Three resonance low frequencies and two acoustic frequencies are considered in different testing scenarios, at increasing levels of excitation amplitude. The results show a general good performance of the technique with the adopted experimental setup, the choice of the probe frequency and the higher level of the pump excitation having a significant impact on its sensitivity.

**Keywords:** Nonlinear Vibro-Acoustic Modulation, Structural Health Monitoring, Damage detection, composite materials

## 1. Introduction

Assessing the integrity of load-bearing structures is one of the major concerns in engineering applications and many non-destructive testing (NDT) methods have been developed to this purpose [1]. Some of them involve inspections by a range of observation techniques, such as x-ray radiography, thermography or shearography [2], while some others exploit the properties of transmission and reflection of ultrasonic waves into the materials [3]. These kinds of techniques are however expensive, time-consuming, and often unsuitable for testing large structural systems and/or advanced heterogeneous materials like sandwich panels or composite laminates. Structural Health Monitoring (SHM) methods based on embedding sensors within the structure may be a viable alternative for damage detection [4, 5]. Vibration-based SHM techniques assume that the modal properties of a damaged structure differ from those of the undamaged one. However, noticeable changes of modal properties are



generally associated with rather high levels of damage, while the detection of comparatively small damage severities typically requires the adoption of more advanced approaches, such as those based on the analysis of the curvatures of the mode-shapes or of the frequency response function [6]. An elastic behavior of both the undamaged and the damaged system is assumed by such methods. In contrast, some SHM techniques focus on the nonlinear phenomena induced by damage. This makes them generally more sensitive to early-stage damage [7-9] whose detection is of primary interest when composite materials are concerned.

Indeed, the presence of defects or cracks perturbs the way an impinging wave propagates in a material, causing the onset of nonlinear features such as hysteretic behavior [10], wave resonance amplitude distortion [11], higher and sub-harmonics [12, 13] frequency mixing effects [14] and non-linearity in the elastic response of the system [15-18]. Among the techniques that exploit the non-linear features induced by damage is the Vibro-Acoustic Modulation (VAM) method, which has been proven to be effective in detecting fatigue cracks in steel beams [19, 20], aluminum specimens [21-23] and pipelines [24] as well as in wind turbine blades [25]. This technique was also applied to detect barely visible impact damage in composite materials [8, 26, 27] and composite sandwich panels [28]. The VAM technique applies simultaneously a low-frequency wave (pump excitation) and a high-frequency wave (probe or carrier excitation) to the test system. The interaction of these two waves leads to modulation effects. The appearance of modulation sidebands, i.e., spectral components around the main high-frequency harmonic, is an index of nonlinearity in the system response and reveals the presence of damage.

When carrying out VAM tests the excitation signals can be provided by means of different actuation methods and the system response captured through different kinds of sensors. Low-profile lead zirconate titanate (PZT) transducers are by far the most common choice for providing the high-frequency excitation [7-9, 26-28] and sometimes also the low-frequency modal excitation [29]. The latter is however more commonly applied by means of piezoceramic stack actuators [27, 28] or, more rarely, through shakers [7]. Shakers as low-frequency actuators in VAM tests were for example adopted in [7, 9, 23] to detect damage modes in aluminium and composite specimens. It can be also mentioned that an instrumented hammer was used in [30] to detect damage in steel specimens. As far as the sensors used to acquire the response in composite materials during VAM tests are concerned, PZT transducers [28] or scanning laser doppler vibrometers [8, 26, 27] are undoubtedly the most used.

An experimental setup including a shaker and an accelerometer, which are instruments typically used in modal vibration-based methods, is adopted in this study to apply the VAM technique for the detection of low-velocity impact damage in a composite laminate beam. In the experimental campaign, an electrodynamic shaker and a piezoceramic transducer were used to generate, respectively, the low frequency flexural excitation and the carrier wave, while a micro-accelerometer was employed to acquire the structural response of the sample. Three resonance low frequencies and two acoustic frequencies were considered for different damage scenarios at increasing levels of excitation amplitude. It is worth noting that modal shakers may provide the power required to excite low-frequency vibration modes of systems, while accelerometers may efficiently measure the out-of-plane vibration response of the structure with the additional advantage of easy and fast removal and installation at different locations. The efficacy of the test setup and the effect of the excitation frequencies on the damage detection capability of the VAM method has been investigated in the study.

## 2. Vibro-Acoustic Modulation

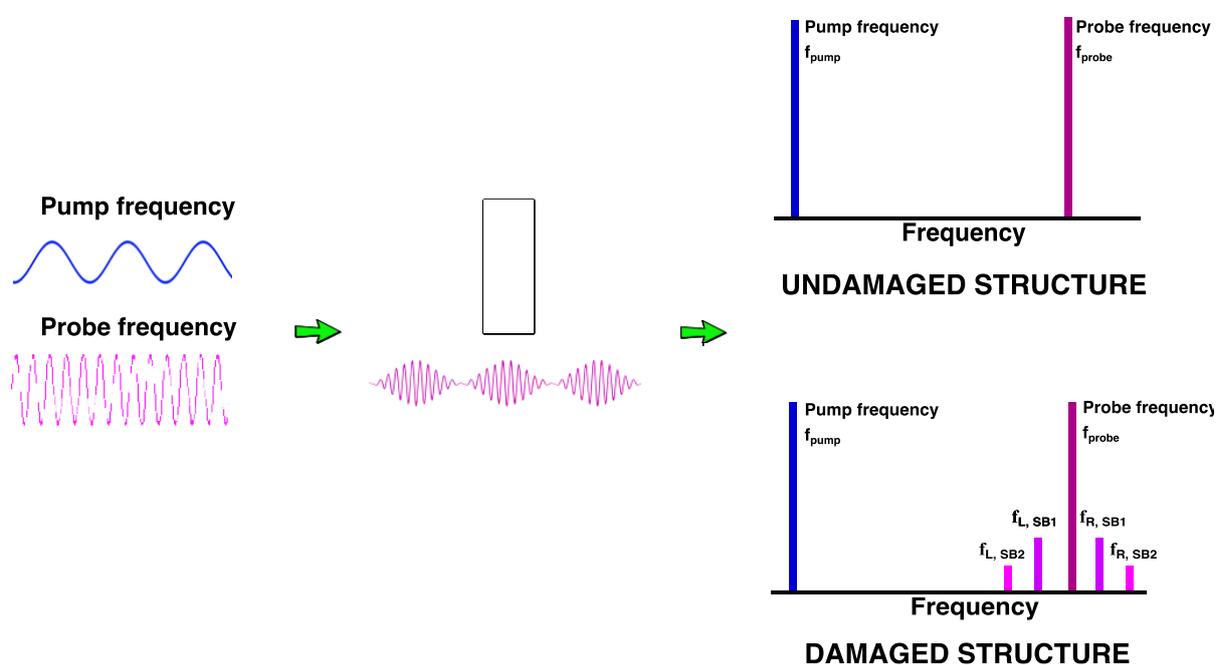
Nonlinear Vibro-Acoustic Modulation (VAM), also referred to as Nonlinear Acoustics [5] or Nonlinear Elastic Wave Spectroscopy [11, 14], was proposed in [31] to detect the presence of closed cracks. In a VAM test the specimen is simultaneously excited by two waves: a low frequency modal/vibration (pump) wave and an acoustic high-frequency (probe) wave. The low-frequency pump wave aims to generate stress within the structure to perturb possible damage, while the high-frequency wave is

expected to sense the variation of stiffness produced by the former, acting as a probing wave that can be modulated by the presence of damage.

As illustrated in figure 1, the spectrum of the signal response of a linear pristine material exhibits only two frequency components corresponding to the probe and pump excitation signals. In contrast, the presence of cracks, damage or discontinuities in the material induces wave perturbations that manifest themselves as additional frequency components (sidebands) around the probing carrier frequency. These sidebands typically occur in pairs (left and right sidebands) at the frequencies:

$$f_{SB_n} = f_{probe} \pm n f_{pump} \quad (1)$$

where  $f_{probe}$  and  $f_{pump}$  are the frequency of the pump and probe waves respectively and  $n$  is a positive integer number.

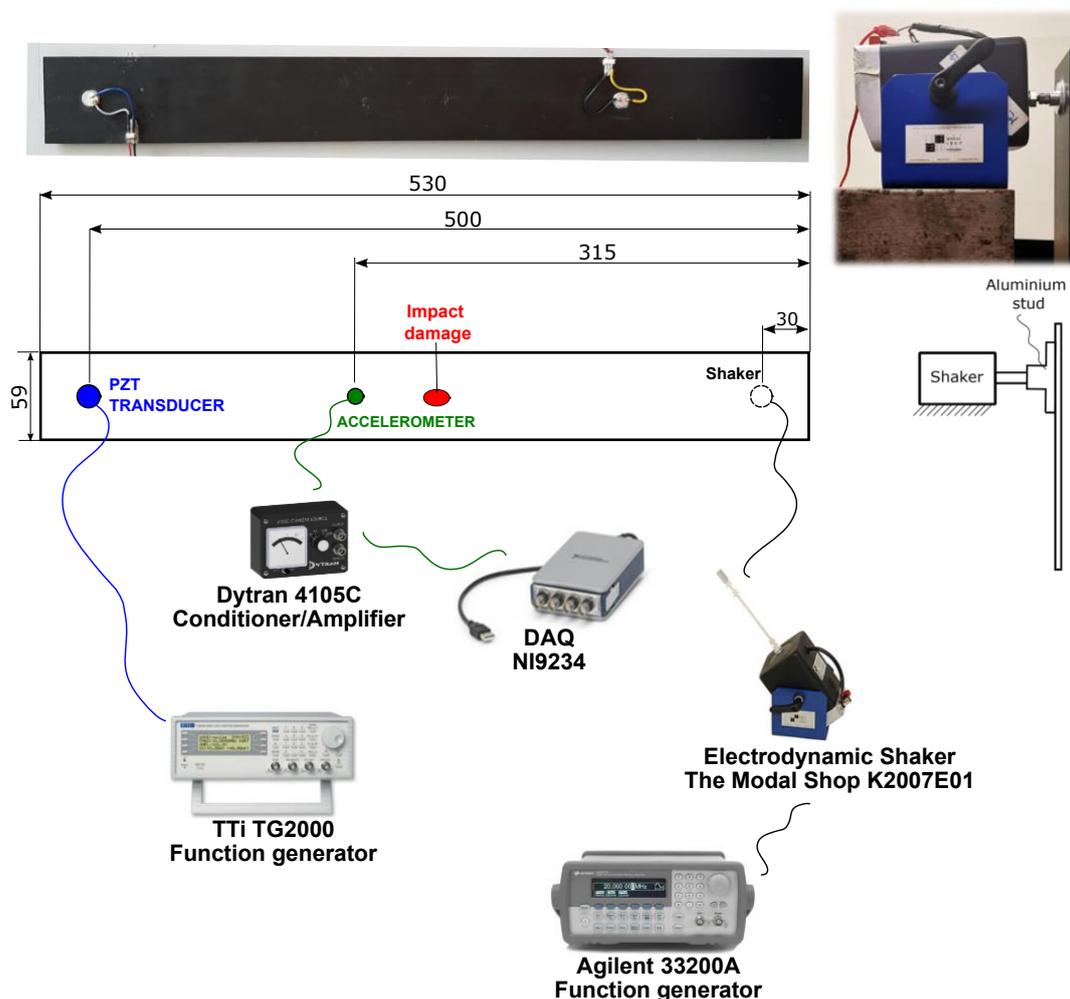


**Figure 1.** Schematic representation of the vibro-acoustic modulation (VAM) technique.

The onset of these modulated frequency components was found to depend on both the presence and the severity of damage and various damage indicators, ranging from the amplitude of the first pair of sidebands to parameters that relate the sidebands amplitude to the amplitude of the probe wave, have been proposed in the literature to monitor the degradation state of a structure. Commonly adopted damage parameters are based, for instance, on the ratio or on the difference between the sum of the amplitudes of the  $i$ -th pair of sidebands and the amplitude of the response at the probe frequency [3, 26, 27]. Further damage indicators involve the comparison between the amplitude of the sidebands and particular functions of the signal amplitudes at the pump and probe frequencies [30].

### 3. Experimental tests

Experimental tests have been conducted on a composite beam made of *Seal Texipreg*®HS160/REM carbon/epoxy prepreg plies laminated with a  $[0/90]_{3s}$  layup and consolidated in autoclave at a pressure of 8 bar and a maximum temperature of 160 °C. The examined sample was a 530 mm x 59 mm beam with a thickness of 2 mm. Prior to testing, the composite beam was ultrasonically C-scanned to exclude the presence of manufacturing defects.



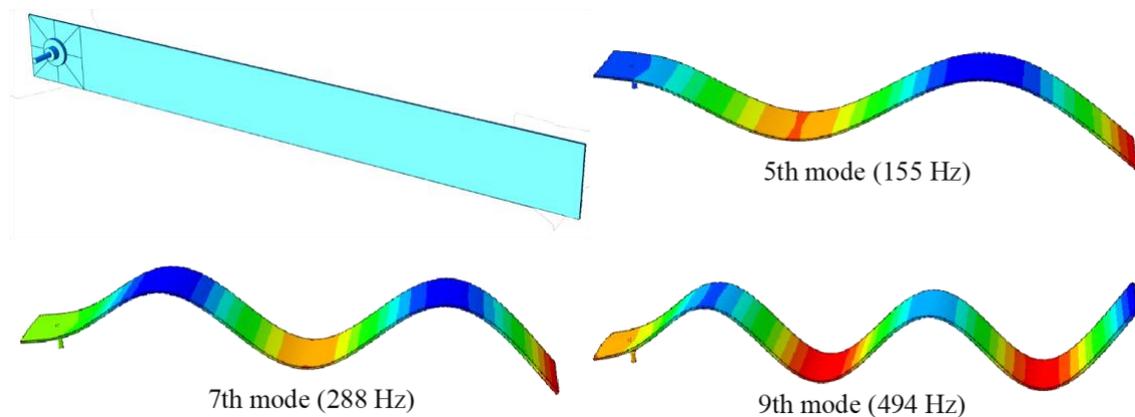
**Figure 2.** Schematic set-up of the vibro-acoustic modulation tests.

The beam was instrumented with a *PI Ceramic PIC 151* low-profile PZT transducer (10 mm diameter and 1 mm thickness) and a *DYTRAN 3224A1* micro-accelerometer, positioned as shown in figure 2. The PZT transducer was bonded to the surface of the beam by means of a two-component epoxy adhesive and wired through welded connectors, while the accelerometer was attached to the beam surface through a thin wax layer.

A drop-weight testing machine, equipped with an instrumented impactor provided with a hemispherical indenter of 10 mm diameter, was used to introduce damage in the sample. Two different levels of damage, referred to as D1 and D2 in the following sections, were obtained by impacting the composite beam with energies of 1.8 J and 2.4 J, respectively. Penetrant-enhanced X-radiographies were taken to characterize the extent and the nature of the two damage levels. As shown in Figure 3, the damage resulting from the impact loads is mainly a combination of matrix cracks and delaminations at various interfaces of the laminated beam. Some minor fibre breakage is however visible at the indentation area after the 2.4 J impact. The projected delamination areas corresponding to the two damage levels are respectively 31.5 mm<sup>2</sup> and 92 mm<sup>2</sup>.

Experimental modal analyses were preliminarily carried out to identify the natural frequencies of the system for subsequent selection of pump and probe frequencies. To this purpose, the laminated composite beam was subjected to a sweep sine excitation, starting from 1 Hz and crossing 1000 Hz in 15 s, generated by a *Modal Shop K2007E01* electrodynamic shaker driven by an *Agilent 33200A* function generator (figure 2). The sample was coupled to the shaker by a threaded aluminium stud that





**Figure 5.** FEM model and numerically predicted mode shapes associated to the three selected pump frequencies.

accelerometer. The power spectrum of the acquired time signal is shown in fig. 4b. In this case, one resonance frequency (7180 Hz) and one generic frequency (6710 Hz) were selected for probe excitation.

Nonlinear vibro-acoustic modulation tests were then performed. A probe (high frequency) sinusoidal signal was applied to the PZT actuator and, simultaneously, the beam was excited with a pump (low frequency) sinusoidal wave by means of the electrodynamic shaker (Figure 2). The amplitude of the probe signal was set to 20 V<sub>pp</sub> for all the tests, while different amplitudes of the low-frequency wave were considered to explore the role of the pump excitation level on the quality of the VAM indications. The experimental tests were carried out for six combinations of pump and probe frequencies, at various amplitudes of the pump excitation, for a total of eighteen different test scenarios. A summary of them is provided in Table 1.

**Table 1.** Test scenarios for different frequency combinations and pump excitation amplitudes

Probe frequency	Pump frequency	Pump amplitudes		
6710 Hz	152 Hz	0.5 V <sub>pp</sub>	1.0 V <sub>pp</sub>	2.0 V <sub>pp</sub>
	282 Hz	2.0 V <sub>pp</sub>	4.0 V <sub>pp</sub>	6.0 V <sub>pp</sub>
	494 Hz	1.0 V <sub>pp</sub>	2.0 V <sub>pp</sub>	3.0 V <sub>pp</sub>
7180 Hz	152 Hz	0.2 V <sub>pp</sub>	0.5 V <sub>pp</sub>	1.0 V <sub>pp</sub>
	282 Hz	2.0 V <sub>pp</sub>	4.0 V <sub>pp</sub>	6.0 V <sub>pp</sub>
	494 Hz	1.0 V <sub>pp</sub>	2.0 V <sub>pp</sub>	3.0 V <sub>pp</sub>

The probe excitation was kept fixed at 20 V<sub>pp</sub>

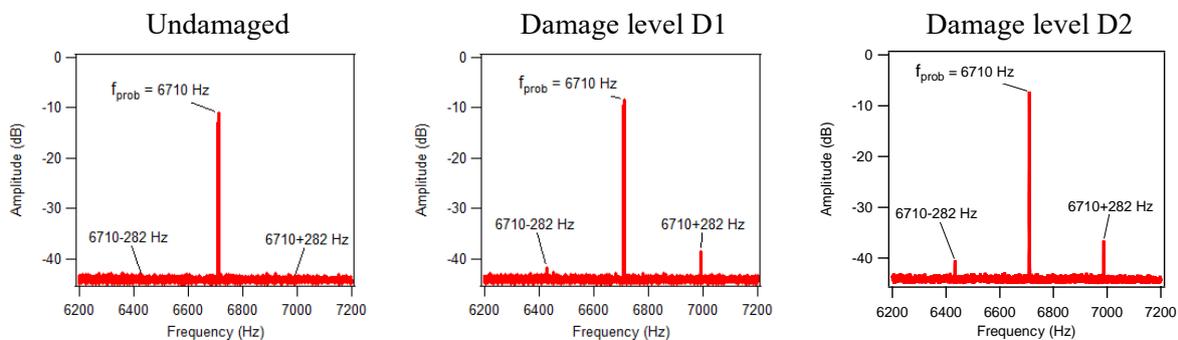
The system response, sensed by the accelerometer, was acquired by the *National Instrument NI9234* digitizer at a 51.2 kSa/s sampling rate. Thirty data sets, each consisting of 256 kpoints, were saved for any of the different scenarios and then post-processed in *Matlab* to calculate the averaged power spectra of the acquired signals. The response spectra were finally zoomed on a window around the carrier wave frequency to retrieve the presence of modulation sidebands.

#### 4. Results and discussion

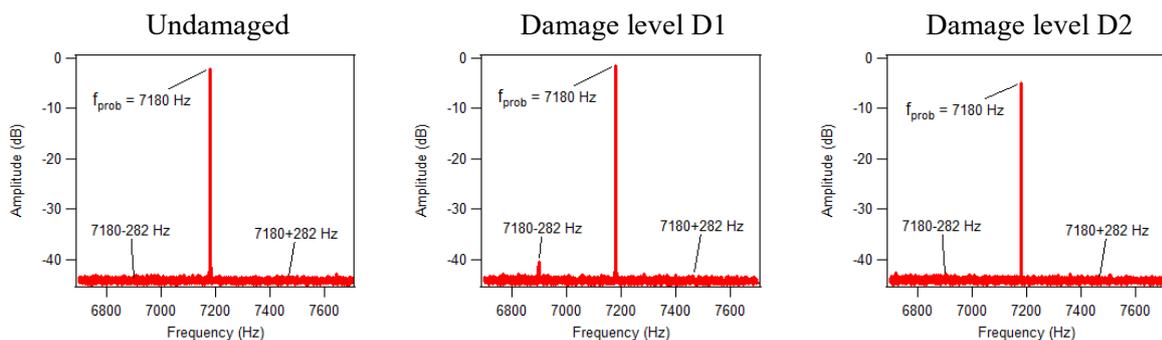
Figures 6 and 7 show, as an example, power spectra around the probe frequency of the undamaged and damaged system responses obtained for two different combinations of vibro-acoustic excitations. The

spectra reported in figure 6 correspond to testing conditions characterized by a pump excitation of  $4 V_{pp}$  at a frequency of 282 Hz together with a simultaneous probe excitation at a frequency of 6710 Hz. Figure 7 shows the spectral response acquired with the beam subjected to the same pump vibration (282 Hz at  $4 V_{pp}$ ) but to a different probe excitation frequency (7180 Hz). It is worth recalling that the same amplitude of  $20 V_{pp}$  was used in all testing scenarios to drive the PZT sensor for probe excitation.

When 6710 Hz is used as probe excitation frequency (figure 6), modulation sidebands appear in the spectral response of the beam after the introduction of the first damage (D1) and the amplitude of these sidebands increases after the beam is subjected to the second impact (damage level D2). In this case the average value of the amplitudes of the left and right sidebands increases of about 50% when advancing from damage level D1 to damage level D2. If we however examine the spectra acquired for a probe excitation frequency of 7180 Hz (Figure 7), we may see that while a sideband first appears on the left of the probe frequency for damage level D1, it then disappears when the severity of damage is increased to level D2. This suggests that, for the same values of excitation amplitudes, the effectiveness of this technique may depend on the selected excitation frequencies.



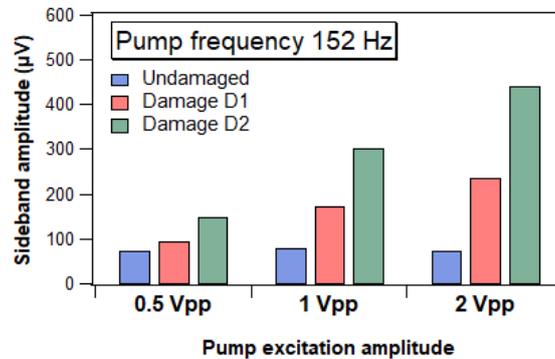
**Figure 6.** Power spectra of the response of undamaged and damaged sample: probe frequency 6710 Hz and pump frequency 282 Hz ( $4 V_{pp}$  amplitude).



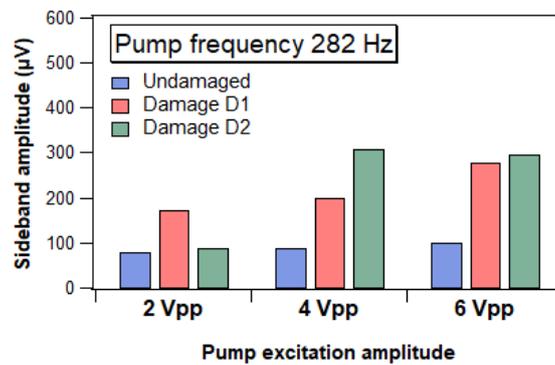
**Figure 7.** Power spectra for undamaged and damaged sample: probe frequency 7180 Hz and pump frequency 282 Hz ( $4 V_{pp}$  amplitude).

The graphs of figures 8 and 9 report a summary of the results obtained for all testing scenarios described in Table 1. The graphs compare the average values of the amplitudes measured at the left and right sideband frequencies for different pump excitation levels when examining the undamaged and the damaged beam. The average amplitude of the sidebands was assumed as an indicator of damage to explore the damage detection capabilities of the VAM approach for different pump and probe excitations.

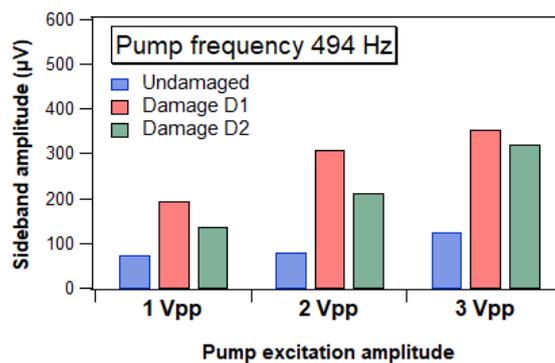
### PROBE EXCITATION FREQUENCY 6710 Hz



(a)



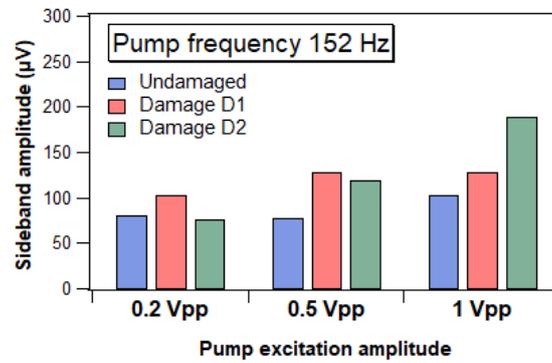
(b)



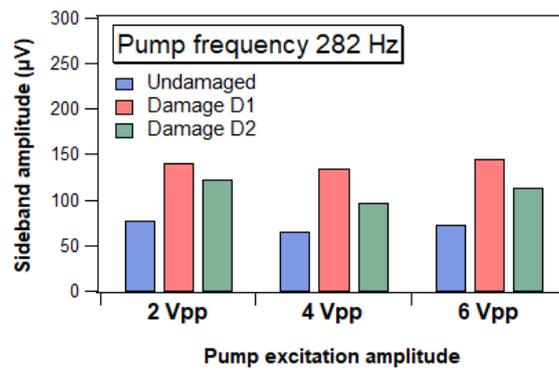
(c)

**Figure 8.** Average sideband amplitudes recorded for the different damage conditions at increasing pump excitation levels. The data plotted in the graphs were obtained using a probe frequency of 6710 Hz and pump frequencies respectively of 152 Hz (a), 282 Hz (b) and 494 Hz (c).

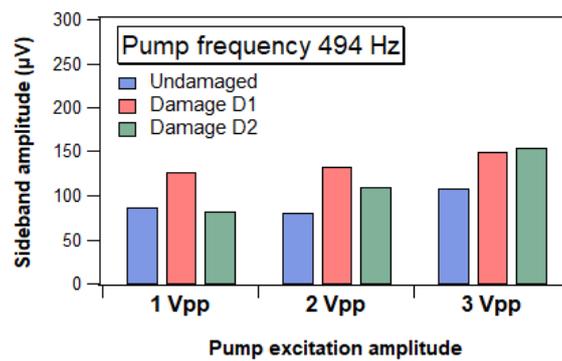
### PROBE EXCITATION FREQUENCY 7180 Hz



(a)



(b)



(c)

**Figure 9.** Average sideband amplitudes recorded for the different damage conditions at increasing pump excitation levels. The data plotted in the graphs were obtained using a probe frequency of 7180 Hz and pump frequencies respectively of 152 Hz (a), 282 Hz (b) and 494 Hz (c).

The data plotted in the graphs show that the VAM technique is generally capable of identifying the presence of the damage introduced in the composite beam by the low-velocity impacts, although, as mentioned before, its efficacy appears to be dependent on the choice of the pump and probe frequencies. The data also show that the choice of a resonance frequency for the probe excitation (7180 Hz) does not necessarily translate into improved detection performances. These indications confirm the findings of previous studies [9, 27], which indeed showed a clear effect of the excitation frequencies on the damage detection capabilities of nonlinear vibroacoustic approaches.

A clear influence of the pump amplitude on the performance of the VAM technique can be also inferred from the present results. If we focus our attention on the data acquired at the maximum pump excitation levels, we observe that the sideband amplitudes measured on damaged conditions are invariably higher than those measured on the undamaged beam. In some cases, however, (see figures 8c and 9b), the level of the sidebands recorded for the larger damage severity (D2) is lower than that recorded for the smaller damage (D1). A possible explanation of these results may be found in the small size of the damaged areas and in the similarity between the features of the two impact-induced damage scenarios, which are both dominated by matrix damage modes, and as such are not expected to lead to large differences in the associated nonlinear wave perturbation mechanisms.

A global comparison of the results obtained across the full range of the examined pump excitation levels shows that the sensitivity to damage of the method decays when the amplitude of the pump vibration is reduced. We notice that in several cases (see for example the graphs of figures 8b, 9a, 9c) the average sideband amplitude recorded for the undamaged beam is comparable or even higher than that measured for the D1 or D2 damaged beam. The loss of sensitivity at low pump excitation amplitudes can be related to the difficulty in the measurement of low-level signals, which can be close to or below the background noise floor, or to the need of attaining a minimum excitation energy for the activation of the mechanisms of nonlinear interaction between the pump and probe waves.

## 5. Conclusions

The detection of early-stage damage in composite materials plays a key role for their safe use in structural mechanics. The non-linear Vibro-Acoustic Modulation (VAM) is a non-destructive technique which can be effective for this purpose, even though some aspects still need to be better investigated to improve the effectiveness of such technique in practical applications. Among them are the role of frequency and amplitude of the pump and probe excitation waves as well as the impact of the testing setup. As a contribution to address this matter, the paper presents some experimental results obtained by testing a laminated composite beam, where two different levels of barely visible damage were introduced by low-velocity impacts. The beam was tested by means of an equipment typically adopted in experimental modal testing. It was simultaneously subjected to a harmonic probing excitation, provided through a piezoceramic disk, and a harmonic pump excitation provided by an electrodynamic shaker, able to supply the power required to excite low-frequency vibration modes in both pristine and damaged conditions. A micro-miniature accelerometer was used to sense the system response.

Six combination of pump/probe frequencies and three levels of pump amplitude were considered in the experimental campaign for a total of eighteen different test scenarios, each one involving the acquisition of data for the undamaged case and for the two damaged cases (D1 and D2). The following insights can be drawn from the results of the study.

- i. The damage (typically delamination) associated to low-velocity impacts was found to cause the onset of a pair of sidebands at the left and right side of the probe frequency in the power spectra of the system response. The amplitude of these sidebands was found to generally increase with the severity of damage and the amplitude of the pump wave. However, some exceptions to this behavior called for an exploration of the role of the probe and pump frequencies as well as of the pump amplitude on the sensitivity of this technique. The average amplitude of the first two sidebands was adopted as modulation intensity index to investigate on this matter.

- ii. The selection of the pump modal frequency seemed to affect slightly the results, although the best damage detection performances were generally associated with the lowest pump frequency (152 Hz) among the three considered in this study.
- iii. The sensitivity of the technique was found to be mostly better at the highest pump excitation level for the different pump/probe frequency combinations. In four out of six cases, at the highest pump excitation amplitude the technique was able to correctly rank the severity of damage. The loss of sensitivity at low pump excitation amplitudes can be related to the difficulty in the measurement of low-level signals and/or to the need of reaching a minimum excitation level for the activation of nonlinear wave interaction mechanisms.
- iv. In some of the considered cases the average amplitude of the sidebands recorded for the larger damage severity (D2) was lower than that recorded for the smaller damage (D1). This can be due to the small extent of the damaged area and to the comparable features of the examined damage conditions.
- v. The choice of the probe frequency seemed to have a significant impact on the sensitivity of the VAM technique, as one of the two selected probe high frequencies (6710 Hz) led to generally better detection performances. Setting the probe excitation to a resonance frequency did not improve, however, the damage detection efficacy.
- vi. The experimental setup adopted in this study, which included a shaker to apply the pump harmonic excitation and a micro-accelerometer to sense the response, was found to be suitable for the application of the VAM technique to detect damage in composite materials.

It can be concluded that the technique still presents some critical issues related to the choice of excitation frequencies and amplitudes that need further investigations. This suggests caution in interpreting VAM data for identification of damage of this nature and extent in this class of materials.

## References

- [1] Moore P O 2012 *Nondestructive Testing Handbook* vol 10, in *Overview* 3rd ed. (Columbus: American Society for Nondestructive Testing) p 594
- [2] Rojas-Vargas F, Pasqual-Francisco J B and Hernandez-Cortés T 2020 Applications of shearography for non-destructive testing and strain measurement *International Journal of Combinatorial Optimization Problems & Informatics* **11**(3)
- [3] Wronkowicz A, Dragan K and Lis K 2018 Assessment of uncertainty in damage evaluation by ultrasonic testing of composite structures *Comp. Struct.* **203** 71-84.
- [4] Stepinski T, Uhl T and Staszewski W J 2013 *Advanced Structural Damage Detection: from Theory to Engineering Applications* (Chichester: Wiley) p 352
- [5] Kundu T 2019 *Nonlinear Ultrasonic and Vibro-Acoustical Techniques for Nondestructive Evaluation* (Cham: Springer) p 773
- [6] Porcu M C, Patteri D M, Melis S and Aymerich F 2019 Effectiveness of the FRF curvature technique for structural health monitoring *Constr. Build. Mater.* **226** 173-87
- [7] Aymerich F and Staszewski W J 2010 Impact damage detection in composite laminates using nonlinear acoustics, *Compos. Part A-Appl. S.* **41** 1084-92
- [8] Klepka A, Pieczonka L, Staszewski W J and Aymerich F 2014 Impact damage detection in laminated composite by nonlinear vibro-acoustic modulation *Compos. Part B-Eng.* **65** 99-108
- [9] Klepka A, Staszewski W J, Jenal R B, Szewdo M, Iwaniec J and Uhl T, 2012 Nonlinear acoustics for fatigue crack detection – Experimental investigations of vibro-acoustic wave modulations *Struct. Health Monit.* **11**(2) 197–211
- [10] Bentahar M, El Aqra H, El Guerjouma R, Griffa M and Scalerandi M 2006 Hysteretic elasticity in damaged concrete: quantitative analysis of slow and fast dynamics, *Phys. Rev. B* **73** 014116
- [11] Van Den Abeele K E A, Johnson P A and Sutin A 2000 Nonlinear Elastic Wave Spectroscopy (NEWS) techniques to discern material damage, part I: nonlinear wave modulation spectroscopy (NWMS) *Res. Nondestruct. Eval.* **12** 17-30

- [12] Lissenden C J, Liu Y, Choi G W and Yao X 2014 Effect of localized microstructure evolution on higher harmonic generation of guided waves *J. Nondestruct. Eval.* **33** 178-86.
- [13] Shah A A and Ribakov Y 2009 Non-linear ultrasonic evaluation of damaged concrete based on higher order harmonic generation *Mater. Des.* **30** 4095-102
- [14] Van Den Abeele K E A, Carmeliet J, Cate J A T and Johnson P A 2000 Nonlinear Elastic Wave Spectroscopy (NEWS) techniques to discern material damage. Part II: single mode nonlinear resonance acoustic spectroscopy. *Res. Nondestruct. Eval.* **12**(1) 31-42.
- [15] Scalerandi M, Gliozzi A S, Bruno C L E, Masera D and Bocca P, 2008 A scaling method to enhance detection of a nonlinear elastic response *Appl. Phys. Lett.* **92** 101912.
- [16] Porcu M C, Pieczonka L, Frau A, Staszewski, W J and Aymerich F 2017 Assessing the scaling subtraction method for impact damage detection in composite plates *J. Nondestruct. Eval.* **36** 33
- [17] Loi G, Porcu M C and Aymerich F 2021 Impact damage detection in composite beams by analysis of non-linearity under pulse excitation *J. Compos. Sci.* **5** 39
- [18] Loi G, Porcu M C, Pieczonka L, Staszewski W J and Aymerich F 2019 Scaling subtraction method for damage detection in composite beams *Procedia Struct. Integr.* **24** 118-26.
- [19] Duffour P, Morbidini M and Cawley P 2006 A study of the vibro-acoustic modulation technique for the detection of cracks in metals *J. Acoust. Soc. Am.* **119**(3) 1463
- [20] Yoder C and Adams D E 2010 Vibro-acoustic modulation utilizing a swept probing signal for robust crack detection *Struct. Health Monit.* **9**(3) 257-267
- [21] Sohn H, Lim H J, DeSimio M P, Brown K and Derriso M 2014 Nonlinear ultrasonic wave modulation for online fatigue crack detection, *J. Sound Vib.* **333**(5) 1473-84
- [22] Straka L, Yagpdzinsky Y, Landa M and Hanninen H 2008 Detection of structural damage of aluminum alloy 6082 using elastic wave modulation spectroscopy *NDT E Int.* **41**(7) 554-63
- [23] Dziedzic K, Pieczonka L, Adameczyk M, Klepka A and Staszewski W J 2018 Efficient swept sine chirp excitation in the non-linear vibro-acoustic wave modulation technique used for damage detection *Struct. Health Monit.* **7**(3) 565-76
- [24] Jiao J, Zheng L and Song G 2011 Vibro-acoustic modulation technique for micro-crack detection in pipeline *Proc. SPIE - Int. Soc. Opt. Eng.* **8321**(83213X)
- [25] Kim S et al. 2014 Crack detection technique for operating wind turbine blades using vibro-acoustic modulation *Struct. Health Monit.* **3**(6) 660-70
- [26] Pieczonka L, Zietek L, Klepka A, Staszewski W J, Aymerich F and Uhl T 2017 Damage imaging in composites using nonlinear vibro-acoustic wave modulations, *Struct. Control Health Monit.* **25**(2)
- [27] Frau A, Pieczonka L, Porcu M C, Staszewski W J and Aymerich F 2015 Analysis of elastic nonlinearity for impact damage detection in composite laminates *J. Phys. Conf. Ser.* **628** (1)
- [28] Pieczonka L, Ukowski P, Klepka A, Staszewski W J, Uhl T and Aymerich F 2014 Impact damage detection in light composite sandwich panels using piezo-based nonlinear vibro-acoustic modulations *Smart Mater. Struct.* **23**(10)
- [29] Donskoy D M, Sutin A M and Ekimov A 2001 Nonlinear acoustic interaction on contact interfaces and its use for nondestructive testing *NDT Eval. Int.* **34**(4) 231-38
- [30] Meo M and Zumpano G 2005 Nonlinear Elastic Wave Spectroscopy identification of impact damage on a sandwich plate *Comp. Struct.* **71**(3-4) 469-74
- [31] Zaitsev V Y, Sutin A M, Belyaeva I Y and Nazarov V E 1995 Nonlinear interaction of acoustical waves due to cracks and its possible usage for cracks detection *J. Vib. Control* **1**(3), 335-44