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Scaling Subtraction Method for Damage Detection in Composite Beams

Gabriela Loi[a]*, Maria Cristina Porcu[a], Lukasz Pieczonka[b], Wieslaw Jerzy Staszewski[b], Francesco Aymerich[a]

[a]*Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Piazza d'Armi, 09123 Cagliari, Italy*
[b]*Department of Mechatronics, AGH University of Science and Technology, Al. A. Mickiewicza 30, 30-059 Krakòw, Poland*

Abstract

Composite materials have been widely used in many advanced engineering structures, because of their high strength and good resistance to fatigue and corrosion. Nevertheless, their susceptibility to impact damage is one of the biggest concerns for use in critical load-bearing structures. Over the last few decades, many non-destructive techniques based on the analysis of nonlinear vibrations and other acoustic phenomena have been developed. Among them, the Scaling Subtraction Method (SSM) is an approach used to extract nonlinear features of an acquired signal generated by the response of a system to an impinging wave, in order to reveal effects that can be associated to internal damage. In this paper, the SSM is applied to examine the response of laminated composite beams to the presence of damage induced by low-velocity impact. The composite beams are tested, both before and after impact, under either impulsive or harmonic excitation of different frequencies, selected among the natural frequencies of the beams. Piezoceramics transducers bonded to the surface of the beam are used for both excitation and sensing. For each harmonic excitation case, the linearly scaled reference signal is compared to the response at large amplitude excitation. An extension of the SSM in the frequency domain is proposed in this paper to detect damage under an impulsive excitation, which typically covers a wide range of frequencies. The results show that this pulse-based extension of the method may be a promising option for detection of nonlinearities associated to damage occurring in composite structures.

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* Corresponding author. Fax: +39 070 6755727.
E-mail address: gabriela.loi@unica.it

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1. Introduction

The presence of nonlinear features in the elastic response of a system to an impinging wave is generally considered an indication of the presence of damage, defects or discontinuities. In fact, the perturbation induced by the interaction between the elastic wave and the material inhomogeneity manifests itself in the onset of nonlinear acoustic phenomena, such as the wave amplitude attenuation, hysteretic behavior or resonance amplitude distortion (Bentahar et al. (2006), Van den Abeele et al. (2000), Guyer et al. (1995)).

In the last decades, various nondestructive methods and structural health monitoring techniques have been developed for identifying nonlinear features in the response of a structure and thus obtaining information on the presence of damage. These methods, generally, take into account only a part of the nonlinear signature of the system, such as higher and sub-harmonics (Morris et al. (1979), Shaha et al. (2009), Lissenden and Liu (2014)), sidebands (Meo and Zumpano (2005)), or wave modulation (Dao et al. (2017), Aymerich and Staszewski (2010), Pieczonka et al. (2018)) and frequency mixing effects (Van Den Abeele and Johnson (2000), Porcu et al. (2019)). However, being much smaller than that of the recorded signal, the amplitude of the above-mentioned features may not be easily distinguished from the background noise, especially when early damage is involved. To overcome this limitation and account for the evaluation of the total nonlinear content of the response of the system, the Scaling Subtraction Method (SSM) was recently proposed in Scalerandi et al. (2008). Under the assumption that the response of a system depends on the excitation amplitude, the SSM considers a reference harmonic signal, which has to be linearly rescaled and then subtracted from the acquired signal at different excitation amplitudes in order to point out the nonlinear signature of the system. By referring to the response of the system at selected resonance frequencies, the SSM was found to be more effective than other nondestructive techniques, such as the linear ultrasonic method consisting in measurement of the attenuation or the velocity of an ultrasonic wave (Antonaci et al. (2010)).

While the SSM has been applied to the analysis of damage in granular materials, i.e. masonry and concrete (Scalerandi et al. (2008), Bruno et al. (2009), Antonaci et al. (2010)), very few attempts have been made to assess its sensitivity for damage detection in composite materials (Frau et al. (2015), Porcu et al. (2017)). Moreover, the need for preliminary tests to identify the natural frequencies of the system and the sensitivity of the technique to the selected excitation frequency (Porcu et al. (2017)) can make the SSM procedure cumbersome and time consuming. In order to further explore the potential of the SSM approach, this study investigates the capability of the technique to detect damage in composite materials by using a broadband excitation. To this purpose, a composite beam is subjected, both before and after damage introduction, to either harmonic or impulsive excitation, and the signals acquired through piezoceramic (PZT) sensors are analyzed by the classical SSM approach and a pulse-based extended version of the method, here proposed, to infer the presence of low-velocity impact damage.

2. Scaling Subtraction Method

Based on the hypothesis that the presence of discontinuities remains undetected as long as the energy delivered by an impinging wave stays below a threshold level, the SSM assumes that when the amplitude of a harmonic excitation is low enough, the stationary response of the damaged specimen is similar to that of the undamaged material, meaning that the nonlinear contribution is negligible (Scalerandi et al. (2008), Bruno et al. (2009), Antonaci et al. (2010)). Under these assumptions the recorded signal for a low excitation may be regarded as the linear elastic response of the system, allowing the definition of a reference signal $v_{ref}(t)$ that would correspond to the linear response of an equivalent undamaged system (Antonaci et al. (2010)).

If the response of the system is linear, the signal $v_{ref}(t)$ acquired for an excitation amplitude $A_{high} = k\, A_{low}$ can be written as:

$$v_{ref}(t) = k\, v_{low}(t) \tag{1}$$

where $v_{low}(t)$ is the linear response of the system to an amplitude excitation A_{low} and k is a scale factor.

The SSM detects the occurrence of damage by focusing on the scaling properties of the response of the system (Bruno et al. (2009)), i.e. by comparing the actual signal $v_A(t)$ acquired at the amplitude A_{high} to the linearly rescaled signal $v_{ref}(t)$.

In practical terms, the SSM method consists in exciting the system by a harmonic signal with a low amplitude A_{low} and recording its response $v_{low}(t)$. The amplitude of the excitation wave is then scaled, and the corresponding output $v_A(t)$ acquired, enabling the calculation of the scaled subtracted signal $w(t)$ as the difference between the recorded signal $v_A(t)$ and the linearly rescaled signal $v_{ref}(t)$:

$$w(t) = v_A(t) - v_{ref}(t) \tag{2}$$

According to Scalerandi et al. (2008) and Bruno et al. (2009), the loss of proportionality between response and excitation is caused by three main mechanisms: (1) the generation of higher and sub-harmonics with a consequent redistribution of the elastic energy delivered by the wave; (2) a phase distortion due to the dependence of the wave speed on the material elastic constants, whose reduction is strictly related to the damage severity; (3) an amplitude distortion depending on the width and the shift of the resonance curve.

While the scaled subtracted signal $w(t)$ for a pristine material is expected to vanish, the one obtained for a damaged material should contain all the nonlinear contributions of the system response (Scalerandi et al. (2008), Bruno et al. (2009)), such as those related to amplitude reduction or phase shift (fig. 1).

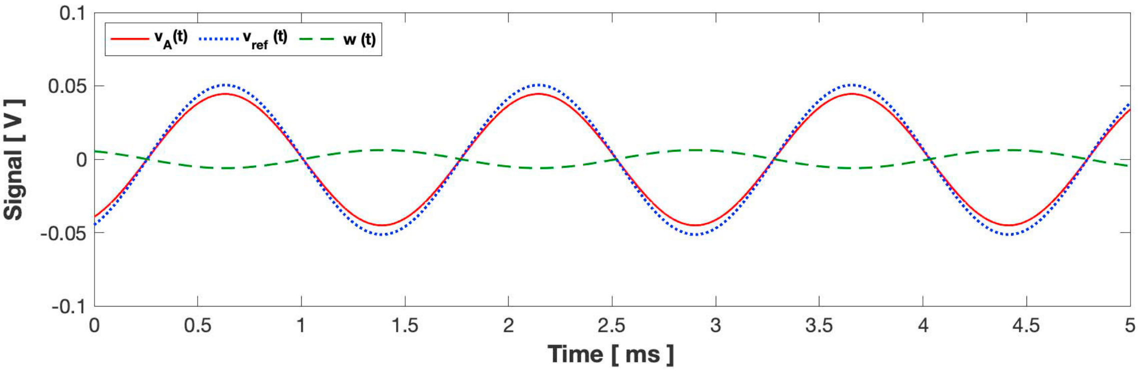

Fig. 1. Plots of acquired signal at high amplitude ($v_A(t)$), linearly rescaled signal ($v_{ref}(t)$) and SSM signal ($w(t)$).

In order to identify and quantify the nonlinear content of the system response through the SSM signal, the following damage indicator was proposed in Scalerandi et al. (2008) and Bruno et al. (2009)

$$\beta = \sqrt{\frac{1}{n}\sum_{i=1}^{n} w_i^2} \tag{3}$$

where n and w_i are the number of acquired samples and the amplitude of the scaled subtracted signal $w(t)$ at each i-th sampling point, respectively.

Following this approach, an attempt was made in this study to assess the effectiveness of an extension of the SSM based on the excitation of the system through a wide range of frequencies by an impulsive signal. In this case, the SSM approach can be applied in the frequency domain, by analysing the frequency components of the acquired signals to compare the actual and scaled reference amplitude values at specific frequencies.

In analogy to the time-based SSM procedure described above, a scaled subtracted amplitude at frequency f can be obtained as

$$Y_{SSM}(f) = Y_A(f) - Y_{ref}(t) \quad (4)$$

where $Y_A\ (f)$ is the amplitude of the FFT of the recorded signal $v_A\ (t)$ for the damaged material and $Y_{ref}\ (f)$ is the FFT amplitude of the reference signal at the frequency f. The $Y_{SSM}\ (f)$ value is thus expected to have a zero value for a perfectly linear material and to increase with amplitude excitation when nonlinearities due to damage occur.

3. Experimental tests

Experimental tests have been conducted on a laminated composite beam manufactured from *Seal Texipreg ®HS160/REM* carbon/epoxy prepreg plies with a quasi-isotropic $[0/\pm45/90]_{2s}$ layup. The sample was a 563 mm x 28 mm beam with a thickness of 2 mm. In order to avoid the presence of nonlinear contributions due to the structural boundaries, the sample was freely suspended using thin nylon cords.

The composite beam was instrumented with three piezoceramic transducers: two low-profile transducers of 10 mm diameter and 1 mm thickness, acting as sensors (*S1* and *S2* in fig. 2) and a *PI PL055.31* stack actuator, used for excitation (A in fig. 2). The signal produced by a *TTI TG5011A* function generator, amplified 20 times by a *PI E501.00* high voltage linear amplifier, was used to drive the stack actuator. The signals from the piezoceramic sensors were acquired with a 14 bit, 100 MHz PC-controlled oscilloscope (*Cleverscope CS328A*).

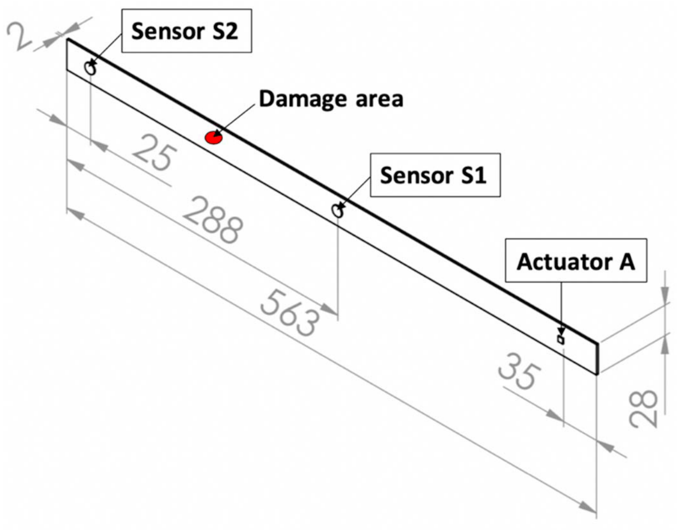

Fig. 2 Scheme of the instrumented composite beam (dimensions in millimeters).

The tests were carried out on the instrumented composite beam first on pristine (undamaged) condition and, subsequently, after the introduction of a typical barely visible impact damage (BVID) by a transverse impact load. To this purpose, the beam was subjected to a 1.7 J impact by means of a drop-weight testing machine, equipped with an impactor with a flat face indenter of 5 mm diameter. The internal damage, characterized by penetrant-enhanced X-radiography, consists of a combination of delamination, fiber fracture and matrix cracks, as shown in fig. 3.

In a first series of tests, the beam was subjected to a pure-tone harmonic excitation generated by the stack actuator and the system response was acquired at the S1 and S2 sensors. Test frequencies for harmonic excitation were chosen among the natural frequencies of the system, determined through a classical modal analysis conducted on the intact specimen. Three resonant frequencies (1580 Hz, 3915 Hz and 10530 Hz) were selected for the analysis. The beam was excited with amplitudes ranging from $A_{low} = 1\ V_{pp}$ to $A_{high} = 12\ V_{pp}$ (with amplitude referring to the output of the function generator) and the signals from sensors S1 and S2 were acquired at a sampling frequency of 267 kHz and on

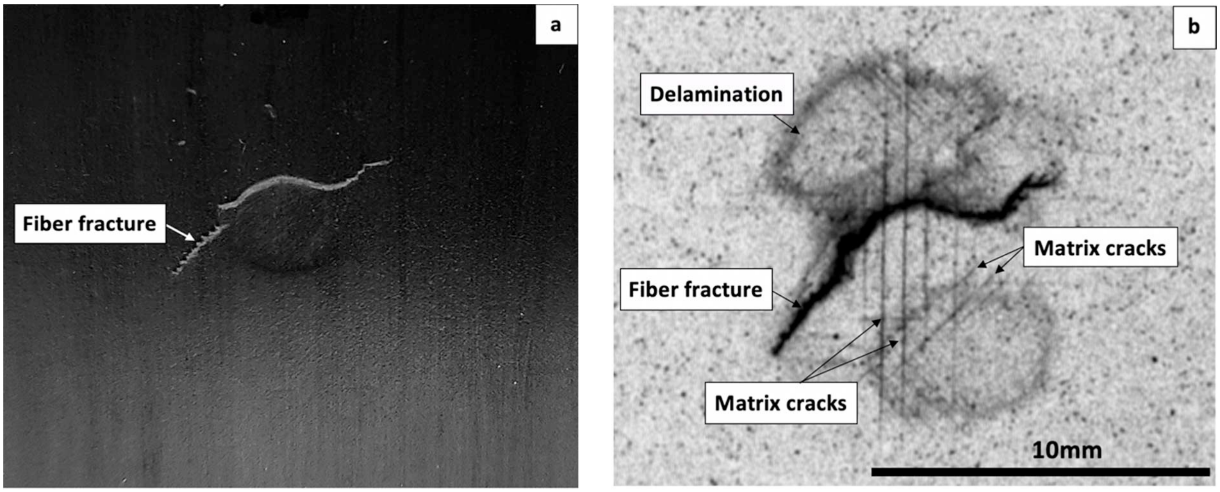

Fig. 3. Impacted region (a) and X-Radiograph of internal impact damage (b)

a time window of 15.3 s. The recorded data were finally post-processed to calculate the scaled subtracted signal *w(t)* and the damage parameter β, according to eqs (2) and (3), respectively.

In a second series of tests, the beam was excited by a pulse signal with width, rise and fall time chosen to cover a frequency range between 0 and 25 kHz, as shown in the spectrum of fig. 4a. The beam was excited by driving the stack actuator with pulse signals with amplitudes ranging from A_{low}=1 V to A_{high} = 12 V and the response of the beam was again recorded by the S1 and S2 sensors. Averaged spectra were finally calculated from 40 datasets of the acquired signals, see fig. 4b. To account for the slight change in frequency content of the pulse driving signals with increasing excitation, the amplitude values extracted from the spectra of the intact sample at selected frequencies were used to define the reference excitation levels $Y_{ref}(f)$. Based on this assumption, the damage indicator $Y_{SSM}(f) = Y_A(f) - Y_{ref}(f)$, see Eq. (4), was used to reveal the nonlinearities in the response of the damaged beam with respect to that of the intact beam, which was assumed as the baseline (undamaged) condition.

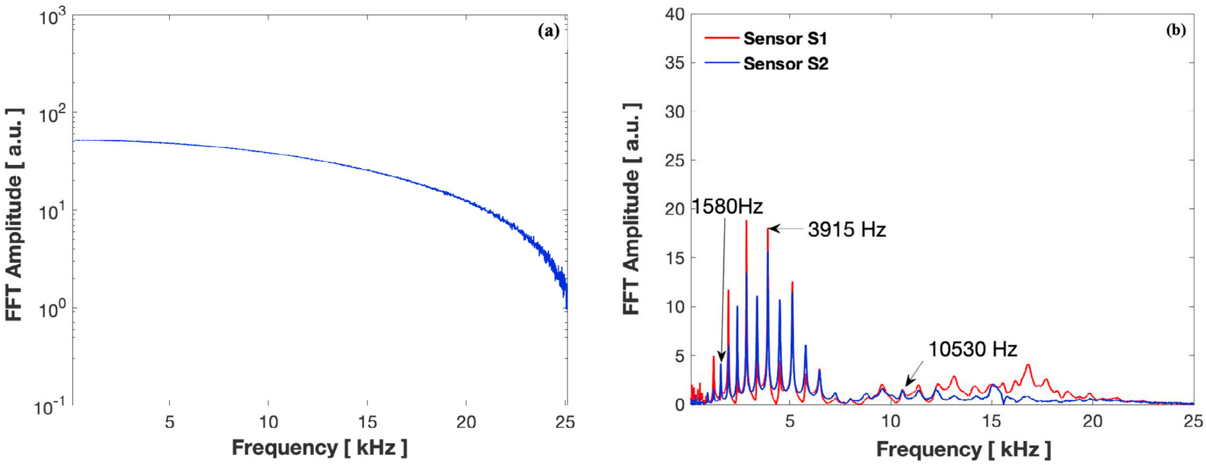

Fig. 4. Spectra of pulse excitation (a) and system response (b)

4. Results

Figures 5-7 plot the values of the SSM damage indicator β obtained for harmonic excitations at three different frequencies (1580 Hz, 3915 Hz and 10530 Hz) as a function of excitation amplitudes. Lines with circle or square markers are used to distinguish between results obtained from data acquired by sensor S1 or sensor S2, while empty and filled markers denote the intact and the damaged case, respectively.

It can be observed that the damage indicator β increases rapidly as the excitation increases in amplitude whatever the test frequency and the sensor examined. However, the indicator β does not vanish for the undamaged pristine beam. This effect might be attributed to the presence of internal defects or inherent (non damage-related) nonlinearities in the material, as well as to intrinsic nonlinearities of the instrumentation.

The results of the analyses show that while for some of the excitation frequencies the presence of impact damage may be clearly detected by comparing the β values for the damaged and undamaged conditions (see for example the plots of fig. 5 and fig. 7, relevant to 1580 Hz and 10530 Hz excitation frequencies), for an excitation frequency of

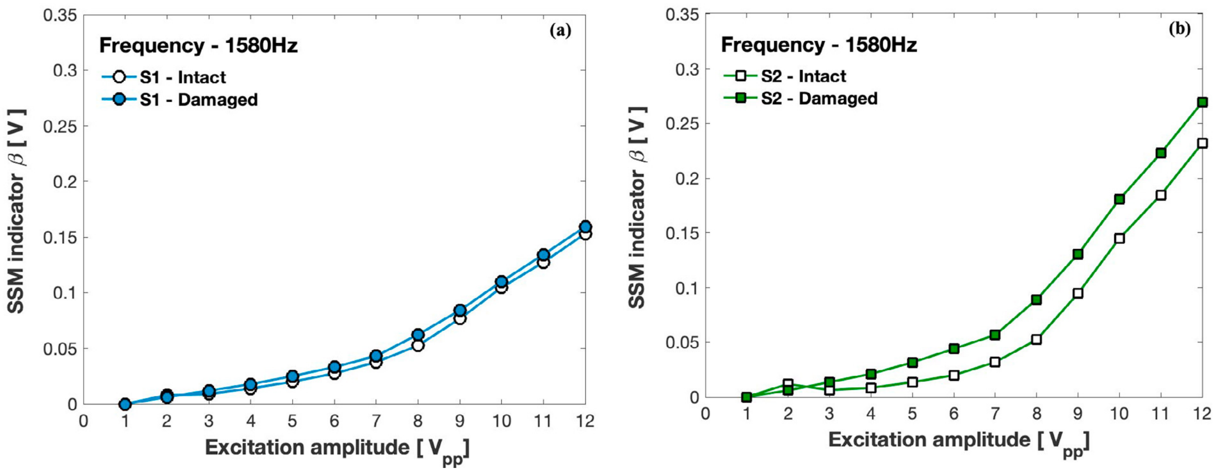

Fig. 5. SSM damage indicator at increasing excitation amplitudes for sensor S1 (a) and sensor S2 (b). Excitation frequency = 1580 Hz.

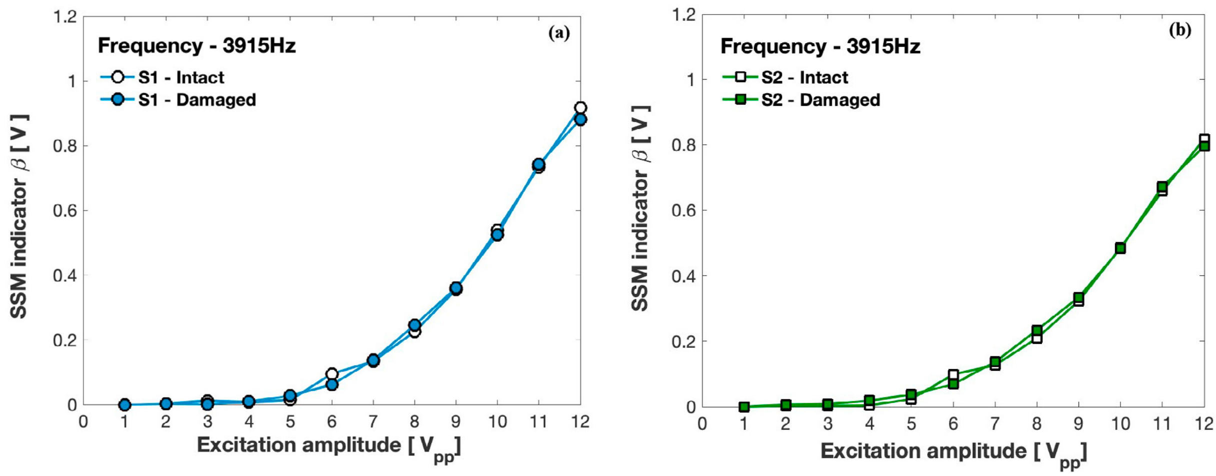

Fig. 6. SSM damage indicator at increasing excitation amplitudes for sensor S1 (a) and sensor S2 (b). Excitation frequency = 3915 Hz.

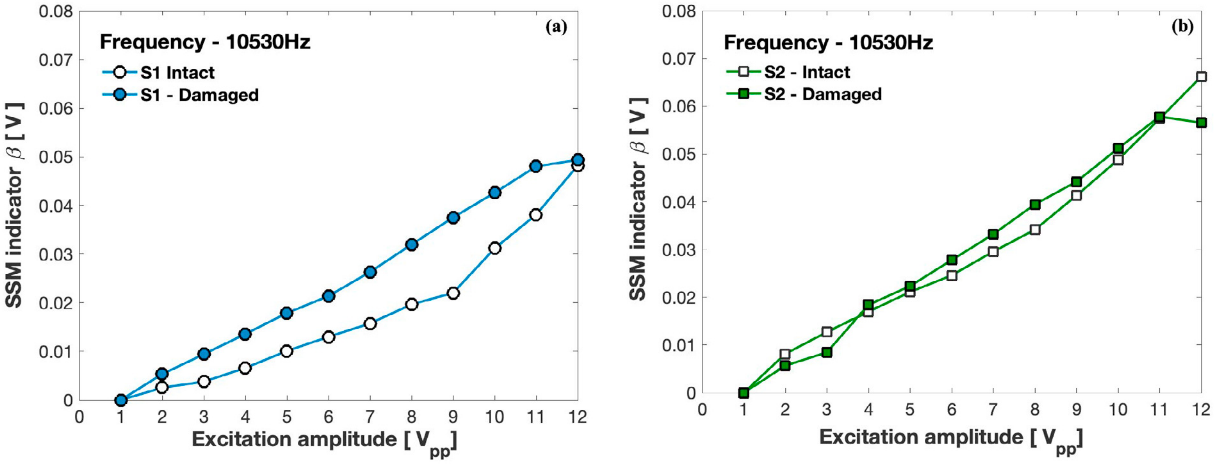

Fig. 7. SSM damage indicator at increasing excitation amplitudes for sensor S1 (a) and sensor S2 (b). Excitation frequency = 10530 Hz.

3915 Hz, the SSM technique is not able to reveal the presence of damage, as shown by the plots of fig. 6. We may further observe that the effectiveness of the method for damage detection also depends on the location of the sensor, as shown by a comparison of the plots of fig. 7a and 7b. These findings confirm the observations of previous studies (Frau et al. (2015), Porcu et al. (2017)), which showed that the effectiveness of the scaling subtraction method is affected by the excitation frequency and by the location of sensor and exciter.

The graphs of figures 8-10 report the results obtained for the second series of experimental tests, in which an impulsive signal was used to excite the beam. In these graphs, the damage indicator Y_{SSM} calculated at the frequency f is plotted as a function of the excitation level, defined here, as described in section 2, as the amplitude at the selected frequency f of the signal recorded on the intact beam. The damage indicators Y_{SSM} were calculated at the same frequencies used for the tests with a pure-tone harmonic excitation (i.e. 1580 Hz, 3915 Hz and 10530 Hz).

The plots show that for all examined frequencies and for both sensors there is a general increase in the value of the damage indicator with the excitation level, even though noticeable scatter is visible in a few cases. The proposed approach may thus provide useful information on the damage state of the system without requiring a previous

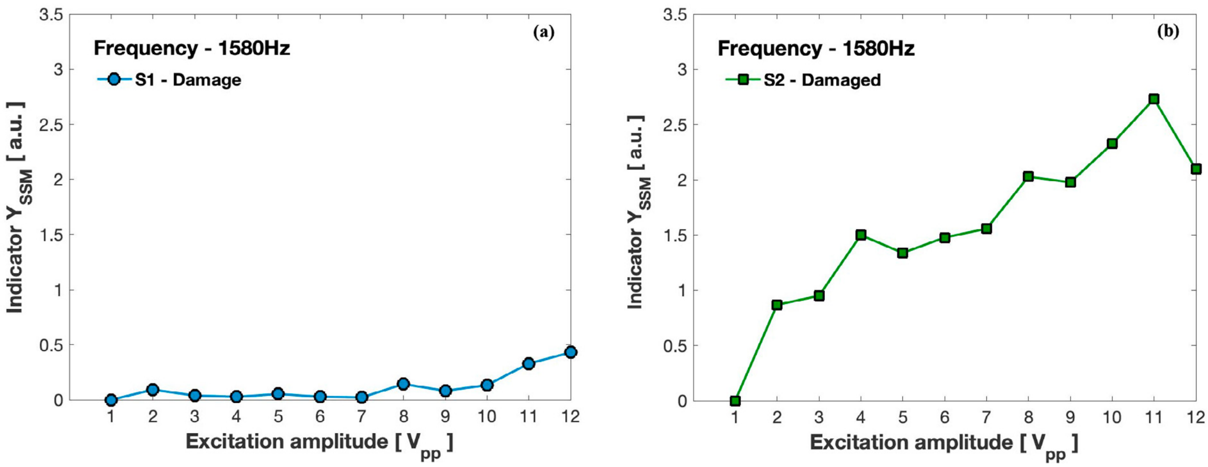

Fig. 8. Y_{SSM} (f = 1580 Hz) indicator at increasing excitation amplitudes for sensor S1 (a) and sensor S2 (b).

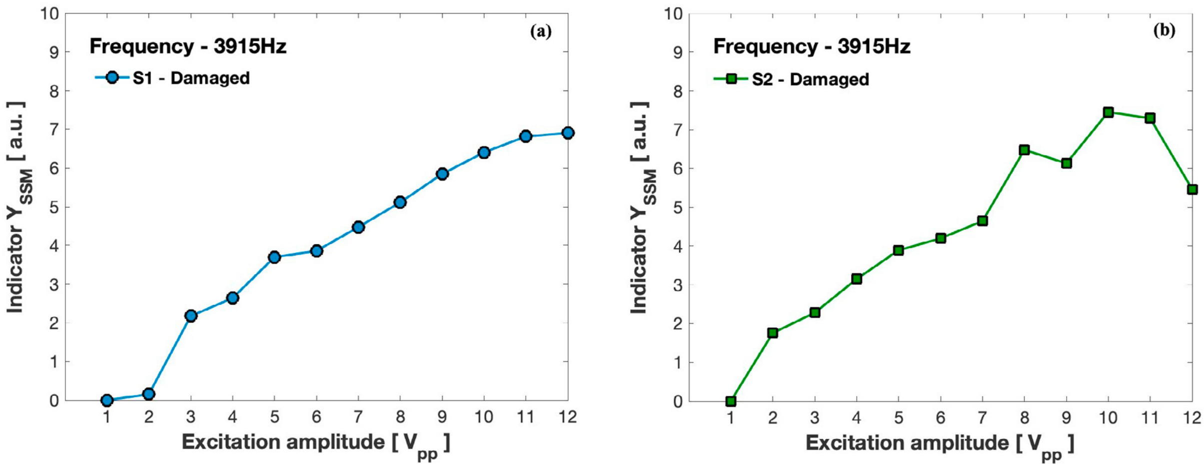

Fig. 9. Y_{SSM} (f = 3915 Hz) indicator at increasing excitation amplitudes for sensor S1 (a) and sensor S2 (b).

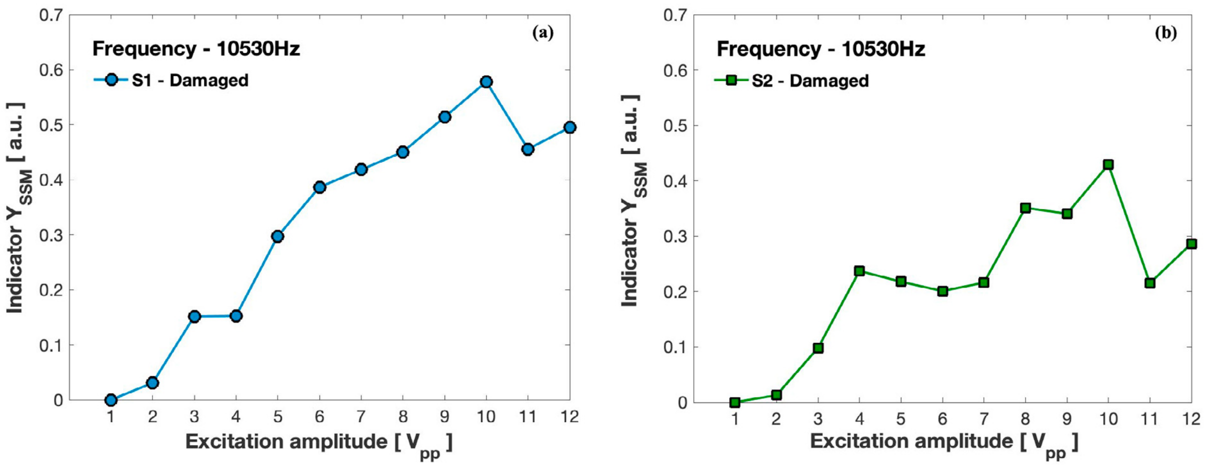

Fig. 10. Y_{SSM} (f = 10530 Hz) indicator at increasing excitation amplitudes for sensor S1 (a) and sensor S2 (b).

characterization of the natural frequencies of the structure, as usually required by the classical application of the SSM. It is especially worth noticing that the presence of internal damage in the material is detected also for the frequency *f*=3915 Hz (fig. 9), at which, in contrast, no clear difference between the response of the undamaged and damaged beam can be observed by the SSM analyses with harmonic excitation, see fig. 7.

5. Conclusions

The effectiveness of the SSM for detection of internal damage in a composite beam was compared to that of a proposed extension of the method that makes use of an impulsive excitation and examines the amplitudes of the spectrum components of the system response at specific frequencies. In the study, a laminated composite beam was tested under either pure tone harmonic or impulsive excitation in both intact and damaged conditions. Barely visible impact damage was introduced in the material by subjecting the beam to a 1.7 J impact energy.

The results of the study show that the sensitivity of the SSM is strongly dependent on the frequency of the excitation and affected by the position of the sensor; in particular, the technique was able to detect the damage introduced by the impact for two of the excitation frequencies considered in the analyses (3915 Hz and 10530 Hz), while no clear evidence of internal damage could be achieved when exciting the beam with a 1580 Hz frequency.

When the beam is excited by a pulse, in contrast, the presence of damage may be revealed by the damage indicator Y_{SSM} at all the three frequencies considered. These results show that the proposed approach could be a promising option for detection of nonlinearities associated to damage occurring in composite structures. Further analyses are however required to explore and characterize the sensitivity and the potential of the proposed pulse-based damage detection approach in the presence of different types and severities of internal damage and for structures with different geometries and laminate layups.

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