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Abstract

The vibro-acoustic modulation method is applied to a composite skin-stiffener structure to investigate the possibilities to utilise this method for damage identification in terms of detection, localisation and damage quantification. The research comprises a theoretical part and an experimental part. An impact load is applied to the skin-stiffener structure, resulting in a delamination underneath the stiffener. The structure is interrogated with a low frequency pump excitation and a high frequency carrier excitation. The analysis of the response in a frequency band around the carrier frequency is employed to assess the damage identification capabilities and to gain a better understanding of the modulations occurring and the underlying physical phenomena. Though vibro-acoustic is shown to be a sensitive method for damage identification, the complexity of the damage, combined with a high modal density, complicate the understanding of the relation between the physical phenomena and the modulations occurring.

Keywords : *Vibro-acoustics, composite structures, frequency modulation, phase modulation*

Introduction

A significant research effort has been addressed to damage identification methods for composite materials. The complex (internal) structure and the associated complexity of the failure modes combined with the high demands on the performance of the methods have so far limited the application of monitoring systems for composite materials.

A wide range of technologies can be employed for damage identification purposes [1, 2]. A subset of these technologies utilise the change in structural dynamic characteristics as an indicator for damage. Traditional vibration based methods, relatively easy to implement, but suffering from a limited sensitivity [3,4], often rely on a linear system description, while more recent work also features nonlinear dynamic effects introduced by local defects [5,6]. Potential benefits are reported in terms of sensitivity [7–9] and environmental robustness [10, 11].

A recently introduced nonlinear approach that has been shown to be sensitive to the severity of damage in geometrically complex structures is the nonlinear Vibro-Acoustic Modulation (VAM) method [8, 12, 13]. This approach relies on the modulation of a high-frequency ultrasonic wave ('carrier') by a more intense low-frequency vibration ('pump'). Both excitation signals are applied to the structure simultaneously. The pump signal with frequency f_p excites the structure and any nonlinearity, while the more sensitive carrier signal at a frequency f_c is used to analyze the potential intermodulation effects. The two signals interact such that the carrier signal is modulated by the pump

signal. Hence, the Fourier spectrum of the response does not only show higher harmonics (nf_p and nf_c, with $n \in \mathbb{N}$), but also sidebands around the high frequency component ($f_c \pm nf_p$, $n \in \mathbb{N}$).

The objective of this paper is to analyse the capabilities of the vibro-acoustic modulation (VAM) method for Structural Health Monitoring (SHM) in a composite skin-stiffener structure and to identify the key parameters affecting the modulations. The composite structure exhibits a more complex structure and more complex damage than most of the structures so far analysed using VAM. In addition a time domain analysis rather than a frequency domain analysis is used to be able to make distinction between amplitude and frequency modulation. Finally, a multi-point time domain analysis is presented, extending the commonly applied single point analysis.

1. THEORY OF VIBRO-ACOUSTICS

A generalised quasi-harmonic nonlinear system [14] can be described by a differential equation consisting of a linear and a nonlinear part:

$$\ddot{q}(t) + \omega_0^2 q(t) = -\varepsilon f\left(q(t), \dot{q}(t)\right), \tag{1}$$

where $q(t)$ is the displacement, ω_0 the natural frequency and $f(q(t), \dot{q}(t))$ a nonlinear function. Utilising the perturbation technique, allowed for weakly nonlinear systems, one can derive that for a two-tone forced excitation and a quadratic nonlinearity the following equations are valid:

$$\ddot{q}(t) + \omega_0^2 q(t) = -\varepsilon q^2(t) + F_p \cos\left(\omega_p t + \varphi_p\right) + F_c \cos\left(\omega_c t + \varphi_c\right) \tag{2}$$

$$\mathscr{O}\left(\varepsilon^0\right): \quad \ddot{q}_0(t) + \omega_0^2 q_0(t) = F_p \cos\left(\omega_p t + \varphi_p\right) + F_c \cos\left(\omega_c t + \varphi_c\right);$$
$$\mathscr{O}\left(\varepsilon^1\right): \quad \ddot{q}_1(t) + \omega_0^2 q_1(t) = -q_0^2(t);$$
$$\mathscr{O}\left(\varepsilon^2\right): \quad \ddot{q}_2(t) + \omega_0^2 q_2(t) = -2q_0(t)q_1(t);$$
$$\dots: \quad \dots$$

The solution is a linear combination of harmonic functions with frequencies equal to $n\omega_p$, $n\omega_c$, $\omega_c - n\omega_p$, $\omega_c + n\omega_p$ ($n \in \mathbb{N}$) and a constant term. Isolating the solution in a narrow frequency band around the carrier frequency ω_c gives the reduced narrow band solution $q_{\text{bp}}(t)$:

$$q_{\text{bp}}(t) = \overbrace{A_c \cos\left(\omega_c t + \varphi_c\right)}^{\text{carrier}} + \overbrace{A_{\text{sb}-} \cos\left((\omega_c - \omega_p)t + \varphi_c - \varphi_p\right)}^{\text{lower sideband}} + \overbrace{A_{\text{sb}+} \cos\left((\omega_c + \omega_p)t + \varphi_c + \varphi_p\right)}^{\text{upper sideband}}, \tag{3}$$

in which:

$$A_c = \frac{F_c}{\omega_c^2 - \omega_p^2}, \quad A_{\text{sb}\pm} = \frac{-\varepsilon \dfrac{F_p}{\omega_c^2 \pm \omega_p^2} \dfrac{F_c}{\omega_c^2 \pm \omega_p^2}}{\omega_0^2 - (\omega_c \pm \omega_p)^2}.$$

This analytical solution demonstrates the intermodulation of the carrier response signal with the pump signal. The carrier response is only modulated in amplitude and not in frequency in this case, although other types of nonlinearity can exhibit frequency modulation as well.

2. EXPERIMENTAL WORK

The structure investigated here is a thermoplastic skin-stiffener section, depicted in figure 1, manufactured by Fokker Aerostructures, according to the joining concept explained in [15]. Both the skin and the stiffener are built from 16 individual plies of unidirectional carbon AS4D fiber reinforced thermoplastic (PEKK) material with a $[90/0]_{4,s}$ lay-up. The filler is made from PEKK and contains 20% short carbon fibres.
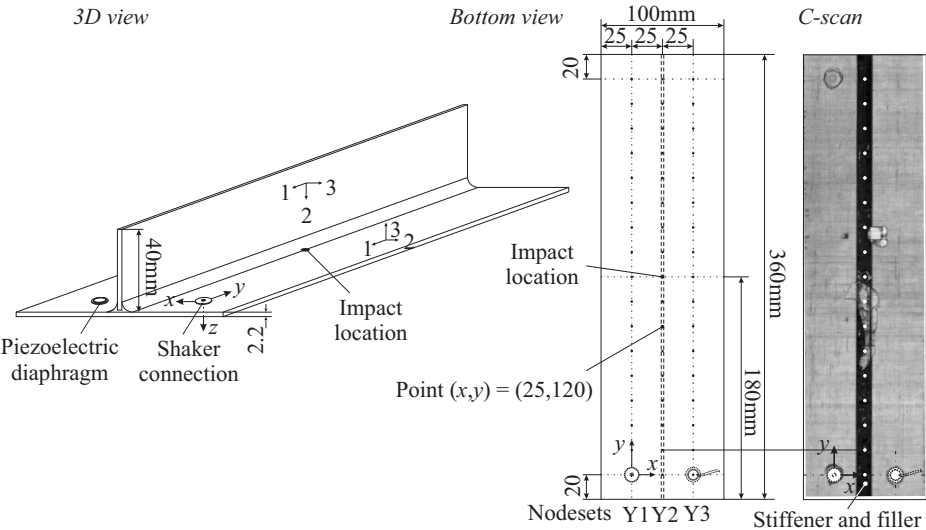
Figure 1: Three dimensional and bottom view of the composite skin-stiffener structure with a butt-joint stiffener. The dimensions, the measurement points (dots) and the impact location are indicated. A C-scan of the structure after impact is displayed on the right.

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An impact damage is introduced to the structure by applying a repeated impact up to 15J, at the location indicated in figure 1. This resulted in a delamination at the skin-stiffener interface and a limited amount of first and second ply failure of the skin. A C-scan of the structure, in which the damage is clearly visible, is displayed on the right side of figure 1.

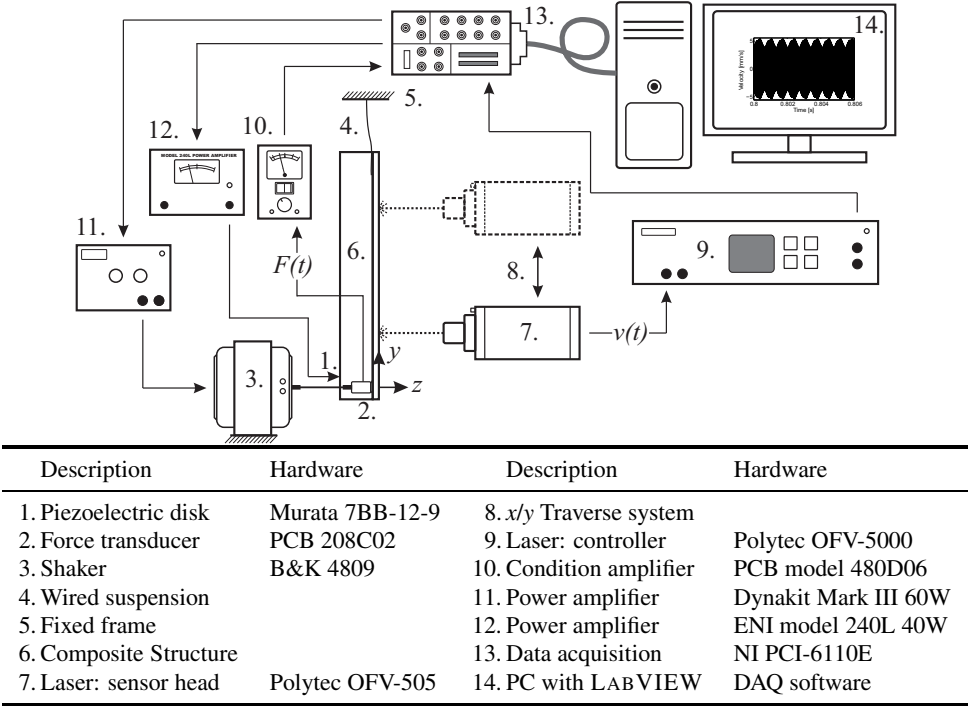| Description	Hardware	Description	Hardware
1. Piezoelectric disk	Murata 7BB-12-9	8. x/y Traverse system	
2. Force transducer	PCB 208C02	9. Laser: controller	Polytec OFV-5000
3. Shaker	B&K 4809	10. Condition amplifier	PCB model 480D06
4. Wired suspension		11. Power amplifier	Dynakit Mark III 60W
5. Fixed frame		12. Power amplifier	ENI model 240L 40W
6. Composite Structure		13. Data acquisition	NI PCI-6110E
7. Laser: sensor head	Polytec OFV-505	14. PC with LABVIEW	DAQ software

Figure 2: Experimental set-up

The composite structure was freely suspended by an elastic wire to isolate it from environmental vibrations. An electromechanical shaker was connected by a stringer and a force transducer to a corner of the structure. The low frequency pump wave was introduced by this shaker, while a piezoelectric diaphragm was glued at another corner of the structure to introduce the high frequency carrier wave. A laser vibrometer, mounted on an x/y traverse system, measured the normal velocities of the skin of the structure at three parallel lines of 17 points each, for a period of approximately 1.05 s (2^{20} samples at 1 MHz). The set-up is schematically shown in figure 2.

Earlier research of the authors [16] revealed that the 4th (1455 Hz) bending frequency exhibits a clear nonlinear response in the region of the delamination. The earlier research focussed on the low frequency part of the response, using a single tone excitation. This research investigates the high frequency part of the response, using a pump wave of $f_p = 1455$ Hz and a weaker carrier excitation at $f_c = 50$ kHz.

3. RESULTS & DISCUSSION

The carrier response and its dominant sideband components are separated from the overall response by applying a bandpass filter within a frequency range of $f_c \pm 10$ kHz. The envelope of the resulting narrow band velocity response clearly exhibits amplitude modulation effects indicating nonlinear components in the signal. These nonlinear modulation effects are extracted by utilizing the Hilbert transform. The periodic behaviour of the instantaneous amplitude $A_{\text{inst}}(t)$ and the instantaneous frequency $f_{\text{inst}}(t)$ for one of the points – $(x,y) = (25, 120)$ mm – underneath the stiffener and located close to the damaged area, are shown in figure 3. Five different shaker amplitudes were used, revealing an increase of the amount of modulation, represented by the peak-to-peak values $\mathcal{M}_a$ and $\mathcal{M}_f$. The time window investigated starts at $t = 0.8$ s, to allow the vibrations of the structure to reach a steady state condition.

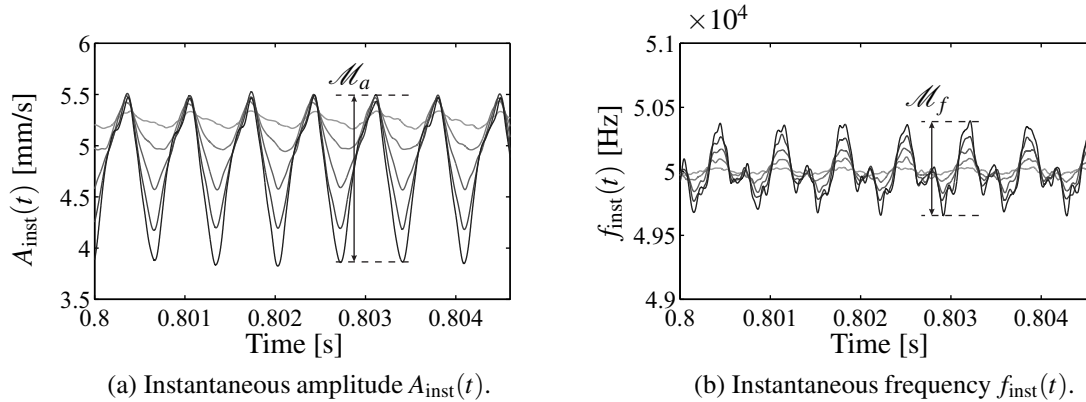(a) Instantaneous amplitude $A_{\text{inst}}(t)$.   (b) Instantaneous frequency $f_{\text{inst}}(t)$.

Figure 3: The instantaneous amplitude (a) and the instantaneous frequency (b) of the bandpass filtered signal, measured at a location close to the damage. Five different shaker amplitudes were used.

The same vibro-acoustic measurement is performed at multiple locations, all directly underneath the stiffener. The local changes in amplitude and phase of the low frequency part of the response, shown in figure 4a, are caused by the damaged skin-stiffener interface as discussed in [16]. The velocity distribution obtained after applying the $f_c \pm 10$ kHz bandpass filter is depicted in figure 4b. The local higher amplitudes between $y = 0.1$ m and $y = 0.16$ m correspond with the location of the skin-stiffener damage. The lower amplitudes at the intermediate region 'II' are due to the incomplete separation of the stiffener and the skin. A more detailed comparison between the geometry of the damage and the bandpass filtered velocity distribution $v_{\text{bp}}(t)$ of the skin at the node line Y2 (see figure 1) is presented in figure 5. This figure shows the excellent correspondance between the bandpass filtered velocity distribution and the geometry of the damage.
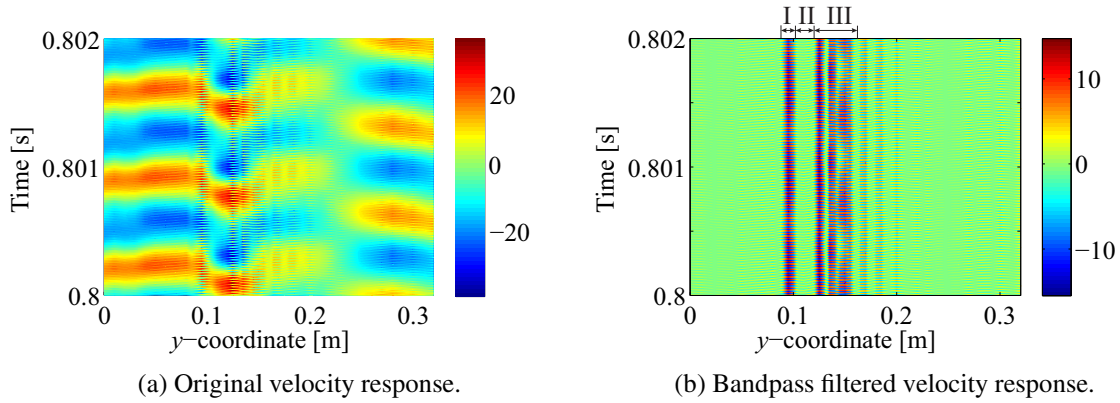
(a) Original velocity response.

(b) Bandpass filtered velocity response.

Figure 4: The original and bandpass filtered ($f_c \pm 10\,\text{kHz}$) velocity responses, for a pump frequency $f_p = 1455\,\text{Hz}$ and a carrier frequency $f_c = 50\,\text{kHz}$, measured at 17 locations underneath the stiffener.

The peak-to-peak values $\mathcal{M}_a$ and $\mathcal{M}_f$ of the oscillations in the instantaneous amplitude and in the instantaneous frequency respectively, are shown in figure 6. The signal exhibits both amplitude and frequency modulation (non zero values for $\mathcal{M}_a$ and $\mathcal{M}_f$). The increased amplitude modulation effects are measured at the damaged area, whereas the there is no direct relation visible between the location of the damage and the frequency modulation. This suggests, based on the single degree of freedom model presented in section 1., a quadratic, displacement related nonlinearity. Evidently, the comparison with the numerical model should be treated with care: firstly, the theoretical analysis is limited to a single degree of freedom and secondly, only a few distinct types of nonlinearities are analysed.
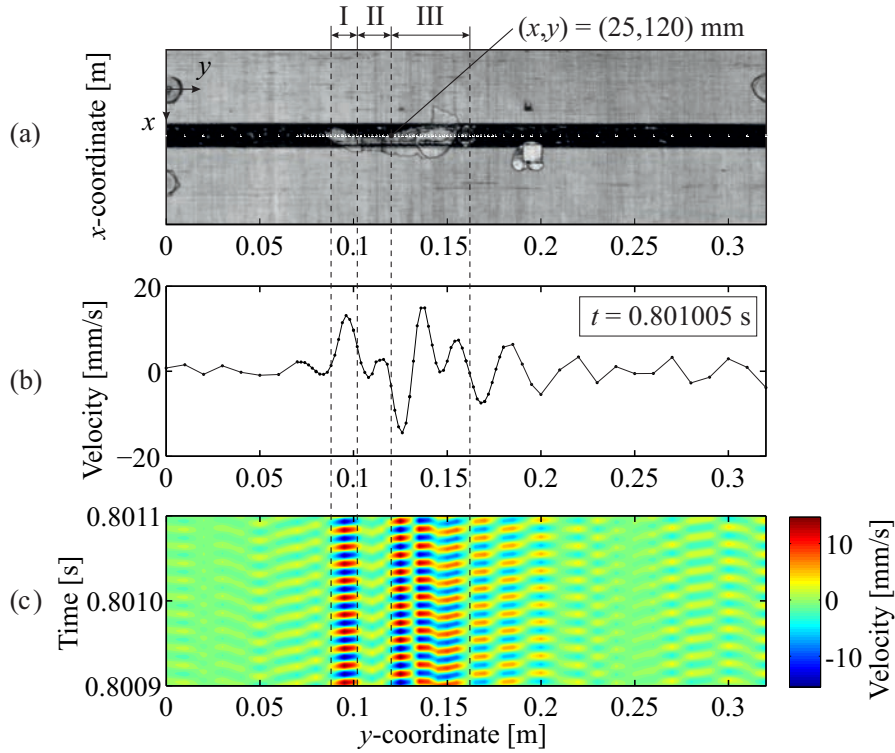

Figure 5: Comparison of the (a) damage location and geometry with the (b,c) bandpass filtered velocity distribution $v_{bp}(t)$ of the skin at node line Y2.
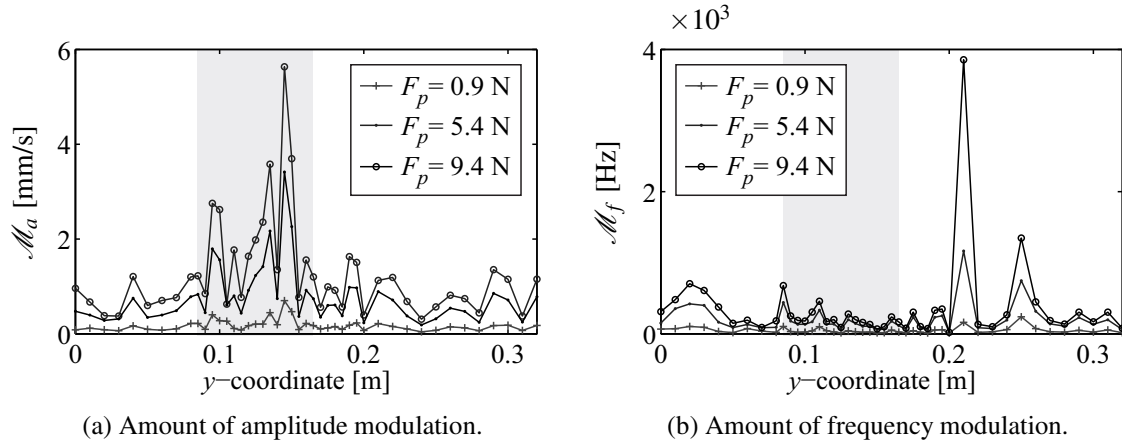
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(a) Amount of amplitude modulation.

(b) Amount of frequency modulation.

Figure 6: The distributions of the amount of amplitude $\mathcal{M}_a$ and the amount of frequency modulation $\mathcal{M}_f$ of the carrier response, measured at 45 locations underneath the stiffener. Three different pump wave excitation levels (F_p) were used. The grey area indicates the damaged region.

The frequency modulation plot (figure 6b) exhibits two high peaks. These peaks are attributed to a local low amplitude of the fundamental carrier response (e.g. near a nodal point) combined with a relatively large amount of amplitude modulation. This can lead to so-called over-modulation effects [17]: the amplitude of the modulation $\mathcal{M}_a$ nearly equals the amplitude of the bandpass filtered velocity response, leading to nearly full modulation and consequently a poor estimation of the instantaneous frequency.

The final, but possibly the most important observation is that the amount of amplitude modulation as well as that of the frequency modulation have a spatial dependency. However, the underlying physical phenomena associated with wave modulations are generally not well understood by researchers [18, 19]. Although the theoretical model provides an understanding of the relevant aspect involved, it is still difficult to find a physical explanation for the modulation behaviour. It was demonstrated in earlier research [16] that the skin-stiffener damage can open and close under a low frequency excitation. Nonlinear behaviour, as was also shown, can also occur when the skin and the stiffener are approaching each other. The same frequencies and amplitudes were used for the pump excitation in the vibro-acoustic experiments. Consequently, the nonlinear skin-stiffener interaction is considered as the most likely explanation for the modulation effects to develop. Combination of the observations of these researches has lead to the formulation of a possible explanation: The carrier wave is more constrained during the phase the skin and the stiffener are in contact, whereas it is less constrained during the phase the skin and the stiffener are not in contact, graphically shown in figure 7. This explains that the amplitude is modulated at the damaged region, whereas the frequency is hardly modulated.

4. CONCLUSION & FUTURE PROSPECT

The results of the vibro-acoustic measurements discussed in this paper, lead to a number of conclusions:

- A distinction between amplitude and frequency modulation can be made by employing a time domain analysis, revealing that in this case the amplitude modulation is larger than the frequency modulation.
- An increase of the amplitude modulation revealed the presence, location and length of the skin-stiffener damage.
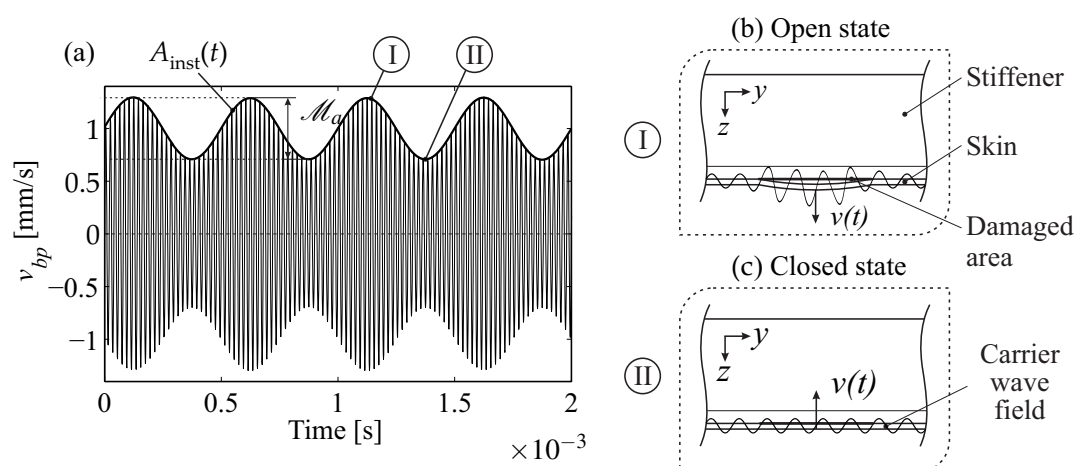- The frequency of the carrier response is hardly affected by the damage investigated.

Figure 7: A simplified and schematic explanation of the (a) carrier modulation principle introduced by the periodic opening and closing of the damage under an intense low frequency pump wave excitation. In the (b) open state, the skin is free to vibrate, whereas the carrier amplitudes are compressed in the (c) closed situation.

- A numerical single degree of freedom model indicates a quadratic nonlinearity in the time dependent displacement field of the structure, although care should be taken when comparing the experimental with the numerical results.
- A plausible explanation for the variation in the amplitude modulation is the variation in the effect of the carrier wave field on the structure with open and closed delamination respectively.

The study demonstrates the potential of the vibro-acoustic modulation based damage identification approach in the time domain. A traditional approach, purely based on sideband amplitudes in the frequency domain does not allow for a separation between the amplitude and the frequency modulation effects and hence it is not able to account for the spatial dependency of the modulation.

The research is currently being developed into the direction of further understanding of the modulations, by means of variational studies. One of the parameters to vary is the carrier frequency, both in amplitude and in frequency. Yoder et al. [10] found a strong correlation between the amplitude of the carrier sidebands and the magnitude of the underlying spectral response of the damaged structure. This is supported by the theoretical single degree of freedom model (see section 1.), but more research is recommended to reveal the physics behind the observations.

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