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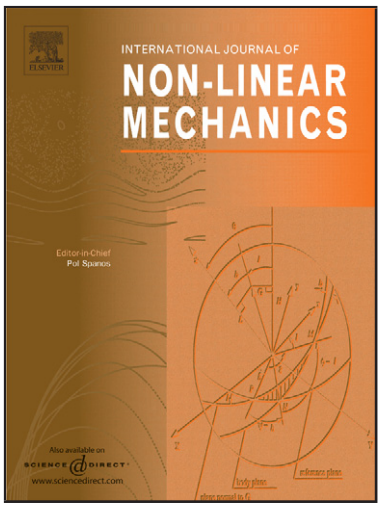

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Understanding the Effect of Boundary Conditions on Damage Identification process when using nonlinear elastic wave spectroscopy methods

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Abstract

This paper presents an experimental campaign aimed at understanding the limitations and capabilities of Nonlinear Elastic Wave Spectroscopy (NEWS) non destructive technique methods (NDT) in the presence of variable boundary conditions. In particular, the objective was to understand if the contact between the structures under investigation and the clamps used to hold the structures could generate non-classical nonlinear effects which could affect the damage detection process by producing false-positive indications of defects presence.
Two different techniques were analysed with varying degree clamping torque. The first approach evaluates the resonance frequency shift as a function of the external load amplitude, and it is called Nonlinear Resonant Ultrasound Spectroscopy (NRUS). The second method used, called Nonlinear Wave Modulation Spectroscopy (NWMS), monitors the generation of sidebands and harmonics when the structure is excited by a double tone external load.
The results showed that the non-classical hysteretical nonlinear effects were dependent on the boundary conditions, highlighted by the presence of resonance shift and harmonics and sidebands in an undamaged sample. This research shows that more work is needed to demonstrate the effectiveness of the methods and the easy-of-implementation in a structural health monitoring system and further research studies and methodology development are needed to discern nonclassical nonlinear effects generated by contacts between mating parts (clamps and sample) from that generated due to the presence of damage.

Introduction

Due to economic reasons, there is a need to extend the life of commercial and military aircraft well past their original design life. However, this gives rise to the urgent need for the development of cost effective NDT techniques to monitor the condition of aircraft structures. The ultimate goal to increase aircraft safety and reduce accidents is to incorporate sensors, actuators and electronics in a structural health monitoring system to monitor and report on the health of the aircraft structure, and to actuate in order to prevent damage or failure of the aircraft structures. This will allow the aircraft operator to move away from costly time-based maintenance procedures toward real-time health condition monitoring allowing timely decisions on preventative and scheduled maintenance before failure occurs.
Currently, a new class of promising NDT techniques, called Nonlinear Elastic Wave Spectroscopy (NEWS), which could be incorporated in a structural health monitoring system, has being developed and it monitors the integrity of structures by analysing the material nonlinear elastic behaviour [1-10] caused by the presence of damage.
The NEWS techniques originally were developed to estimate the nonlinear elastic properties of heterogeneous geomaterial like rocks or sandstones. It has been shown that some damaged materials have a complex compliance and have a nonlinear behavior that cannot be explained with classical nonlinear models [1-2]. The stress strain curve of damaged materials contains terms that describe classical nonlinearity, as well as hysteresis, and discrete memory [2]. Considering stress and strain

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for one dimensional problem, the constitutive relation for wave propagation analysis in quasi static condition can be written as follow:

$$\sigma = \int K(\varepsilon, \dot{\varepsilon})\, d\varepsilon \qquad \textbf{(1)}$$

where σ is the stress, ε is the strain , $\dot{\varepsilon}$ is the time derivative strain and *K* is the elastic modulus. According to the experimental evidence [3-6] one of the possible formulations for the non linear non classical hysteretic elastic modulus is shown in equation (2).

$$K(\varepsilon, \dot{\varepsilon}) = K_0 \left\{ 1 - \beta\varepsilon - \delta\varepsilon^2 - \alpha \left[\Delta\varepsilon + \varepsilon(t)\ sign\ (\dot{\varepsilon})\ + \ldots \right] \right\} \qquad \textbf{(2)}$$

where K_0 is the linear modulus, , β and δ are classical nonlinear coefficients of Taylor expansion of stress versus strain [7-9], α is a material hysteresis measure that takes into account also the history of stress through the terms $sign(\dot{\varepsilon})$, $\Delta\varepsilon$ is the local strain amplitude, represented in equation 3(expression for simple continuous sine excitation [5]) and equation 4:

$$\Delta\varepsilon = \frac{\varepsilon_{\max} - \varepsilon_{\min}}{2} \qquad (3)$$

$$\begin{aligned} \dot{\varepsilon} &= \frac{d\varepsilon}{dt} > 1 \Rightarrow sign(\dot{\varepsilon}) = 1 \\ \dot{\varepsilon} &= \frac{d\varepsilon}{dt} < 1 \Rightarrow sign(\dot{\varepsilon}) = -1 \end{aligned} \qquad (4)$$

The nonlinearity induced by the damage and simulated by this model can be estimated by two groups of methods available for NEWS application: resonance and non-resonance.
Resonance methods analyse the dependence of the resonance frequency on the strain amplitude while exciting the sample at relatively low amplitudes. By observing the relative frequency shift it is possible to have a measure of the internal degradation of the microstructural properties of the material. In Fig. 1 a schematic representation of the method is shown; according with experimental evidence [1-5] the sample under a sweep load centred on one of its natural mode show different behaviour of structural response depending on the status of sample: intact or damaged. These methods, shown in Fig. 1 [2,4], are usually referred to as Nonlinear Resonance Ultrasound Spectroscopy (NRUS) [4]. The resonance methods can be rather labour-intensive and require many readings to be taken (frequency response curves for various excitation levels). Therefore, they may not be suitable for fast in-process measurements.

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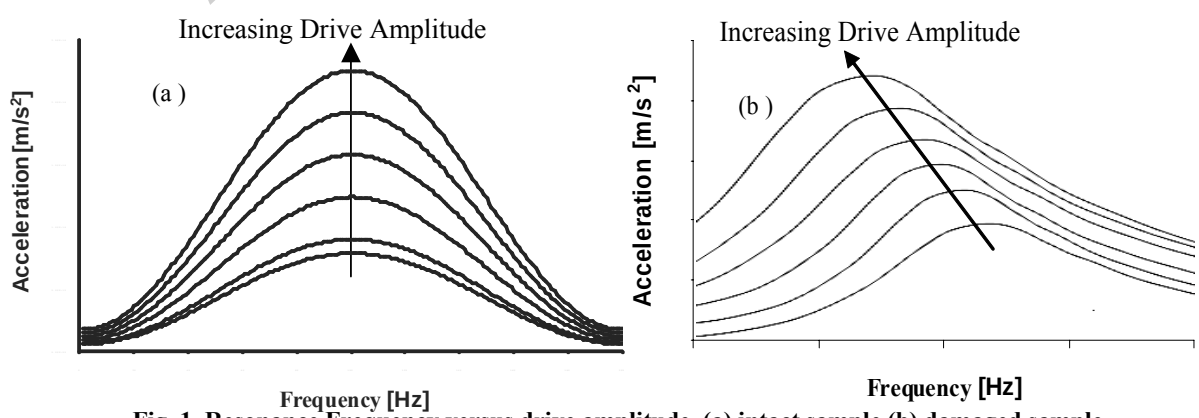

Fig. 1. Resonance Frequency versus drive amplitude. (a) intact sample (b) damaged sample.

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Non-resonance methods are used to study nonlinear effects on elastic waves propagating through the medium. According to the previous experimental work [3,6] and the mathematical model in equations (1) and (2), intermodulation phenomena can be observed in the structural response of damaged material when an excitation as shown in Fig.2 (a) is used. In particular, the excitation is made by the superposition of two sine waves with fundamental frequencies f_1 and f_2 respectively. The spectrum response of the sample is characterized by two effects: the presence of harmonics of both fundamental excitations frequency (nf ; $n=1,3,5\ldots$; for example: $3f_1$, $5f_1 \ldots nf_1$ and $3f_2$, $5f_2 \ldots .nf_2$), and the generation of sidebands around f_2 ($f_2 \pm nf_1$; $n=2,4,\ldots$; for example: , f_2-2f_1, $f_2+2f_1 \ldots f_2-nf_1$, f_2+nf_1) as shown in Fig. 2.

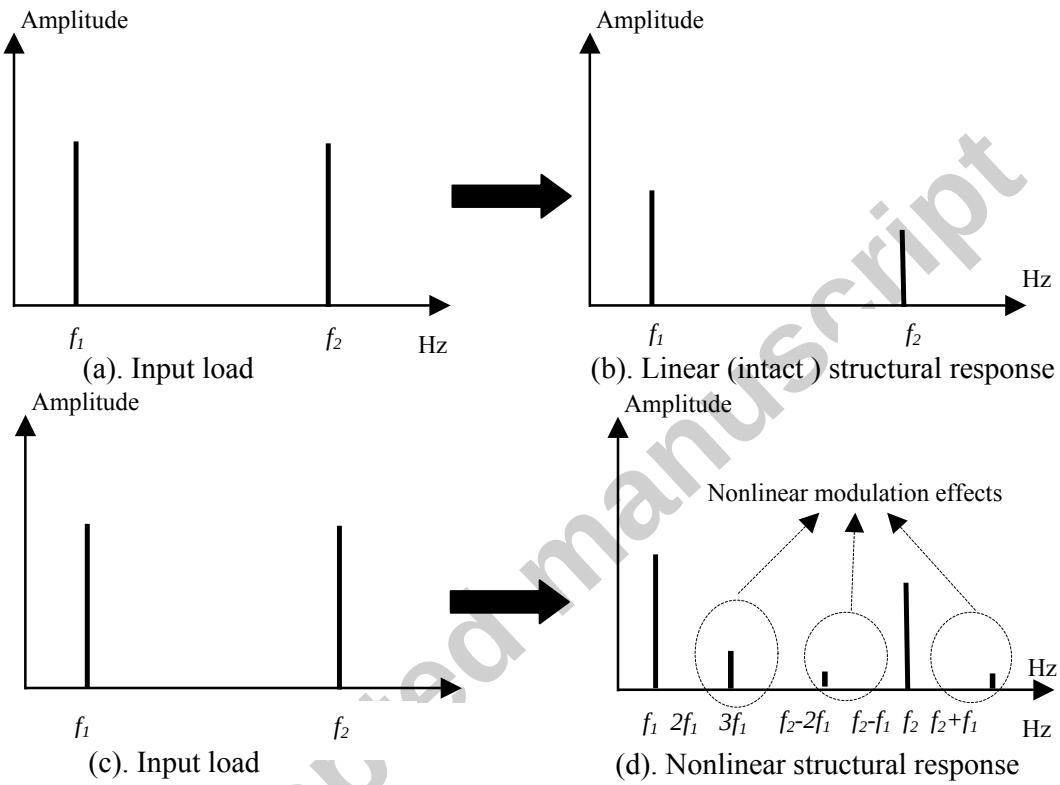

Fig. 2 . Linear and non linear modulation effect. (a) Excitation frequencies. (b) Response of a linear undamaged. (c) Excitation frequencies. (d) Nonlinear response of a damaged material : harmonics and sidebands.

While these two methods have been successfully used to detect impact damage [6,10], the effect of geometrical discontinuities, boundary conditions etc…on the nonlinear response of structures have not been assessed.

In particular, in this paper the effect of the clamp acting on the sample was studied to analyse how boundary conditions may affect the damage detection measures and introduce hysteretical nonlinear effects.

Experimental setup

The test pieces investigated were carbon fibre epoxy composite plates with unknown material properties. The size of the plate size was 210x100x4mm^3 and it was inspected with a C-scan to assess the presence of damage or defects. During this preliminary inspection no damage was found and the specimens appeared in pristine condition. The experimental setup used is shown in Fig. 3. The composite plate was fixed on one side and left free to move on the other end as showed in Fig. 3. Two different values of torque were applied on the bolts (measured with a torquemeter), T_1

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and T_2, in order to analyse the effect of the clamp different on the material nonlinear elastic behaviour. The torque T_1 corresponds to a firmly fixed sample edge, and T_2 was 20% greater then T_1. The plate excitation was obtained by using a low distortion speaker, operating in low and medium acoustic frequency range. The speaker was driven by a signal generator through the power amplifier, and the data was acquired by using an accelerometer and a Brüel & Kjær Pulse system.
The accelerometer (ENDEVCO 27A12) was located at 2 cm from the free short edge and at 5cm from the long edges, on the front face of the plate.

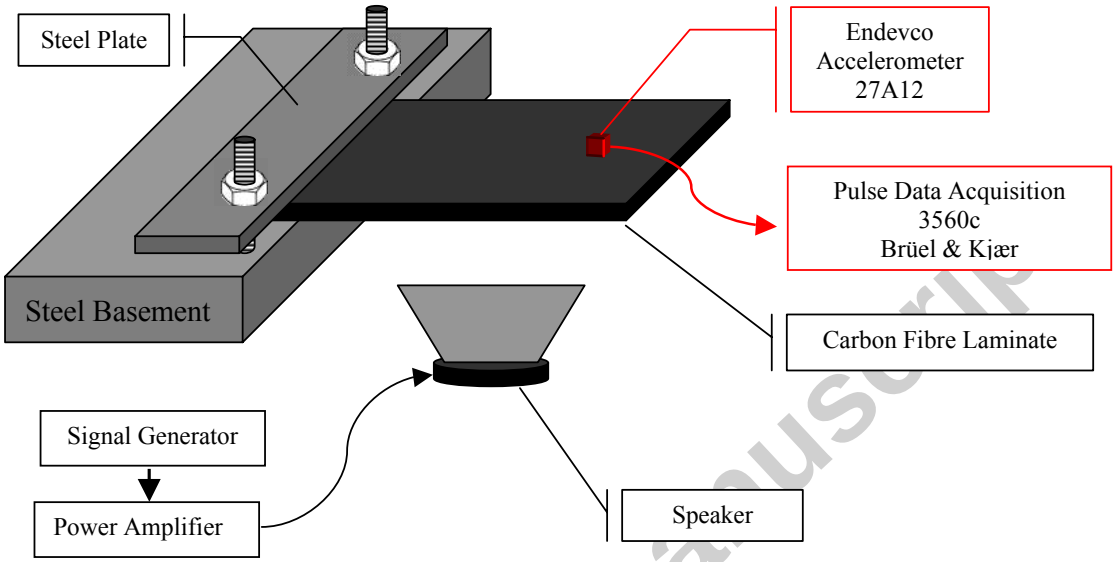

Fig. 3 Schematic representation of equipment configuration.

Two different types of NEWS tests were carried out: NRUS and NWMS [1,6]. The first resonance frequency (flexural mode) for the plates considered was around 200 Hz. The experiments were performed using different drive amplitudes in order to measure the resonance shift versus external amplitude. For the NWMS tests the input signal was the superposition of two sine wave, where the fundamental frequencies (f_1 *and* f_2) are the first and the third resonance modes of the sample ($199<f_1<201$ *Hz*, $2230<f_2<2260$ *Hz*). Different external load amplitudes were tested in order to correlate the non linear phenomena with the external amplitudes.

Results discussion

Two different torque values were applied , ($T_2>T_1$) and the NRUS and NWMS techniques were used. The results of the NRUS test for the two clamps values are shown in Fig. 4.

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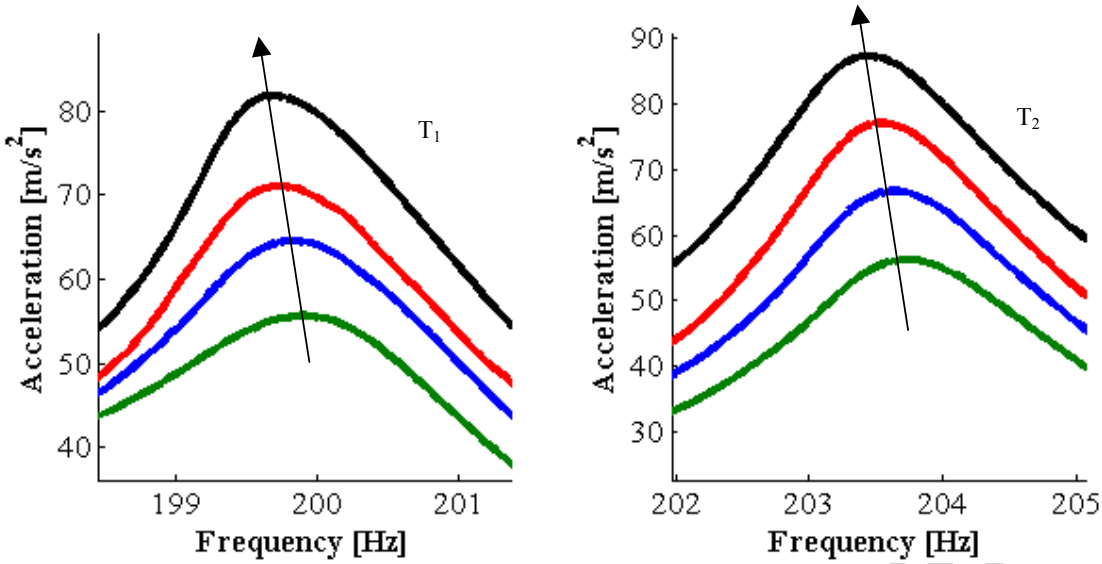

Fig. 4. NRUS tests on one sample with two clamping torque: T_1 and T_2, where T_2>T_1.

The results in Fig. 4 show that in both cases there is a significant shift in the resonance frequency with increasing load amplitude. However, since the same external load was used for both test, when using T_2 as the clamping torque, the value of acceleration amplitude is higher than when using T_1. This behaviour is caused by an increase of the stiffness due to the higher torque used. By measuring the nonlinear hysteretic parameter α (equation 5), an indication of the level of hysteretical nonlinear effects introduced by the contact between the sample and the clamp could be obtained. In a previous work [10] the parameter α was used to estimate relative damage severity, while in this work, α was used to study the effect of the boundary conditions on the damage detection process. The nonlinear hysteretic parameter α was evaluated as follows:

$$\alpha\ \Delta\varepsilon = \frac{f_O - f_i}{f_O} \qquad (5)$$

where Δε is the average strain amplitude, f_0 is the natural frequency of intact sample or the lowest resonance mode measured, f_i is the natural mode measured for each drive amplitude, represented by the maximum value of each curve shown in Fig.4. In Fig.5, the behaviour of parameter α as a function of the acceleration is showed. An increase of the clamp torque causes an increase of the nonlinear parameter, showing that measuring only this parameter may give false data for the damage detection process.

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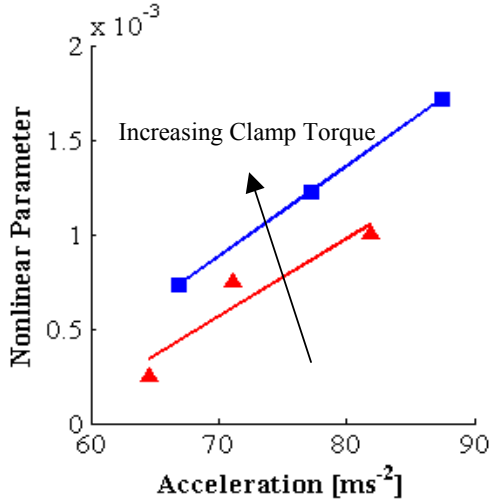

Fig. 5. Non linear parameter versus acceleration. The marker "■" indicates data for torque level T_1 and the marker "▲" indicates data for torque level T_2, where $T_1<T_2$.

Various other amounts of clamping torque were studied and similar conclusions were drawn.
In Fig. 6 and Fig. 7 the spectra of the accelerations measured with the NWMS test are shown for both clamp conditions. Different amplitudes of external loads were used in order to correlate the amplitude of nonlinear features versus the structure linear response, represented by fundamental amplitude. The generation of nonclassical nonlinear hysteretical features is clearly observable as highlighted by the presence of harmonics and sidebands.

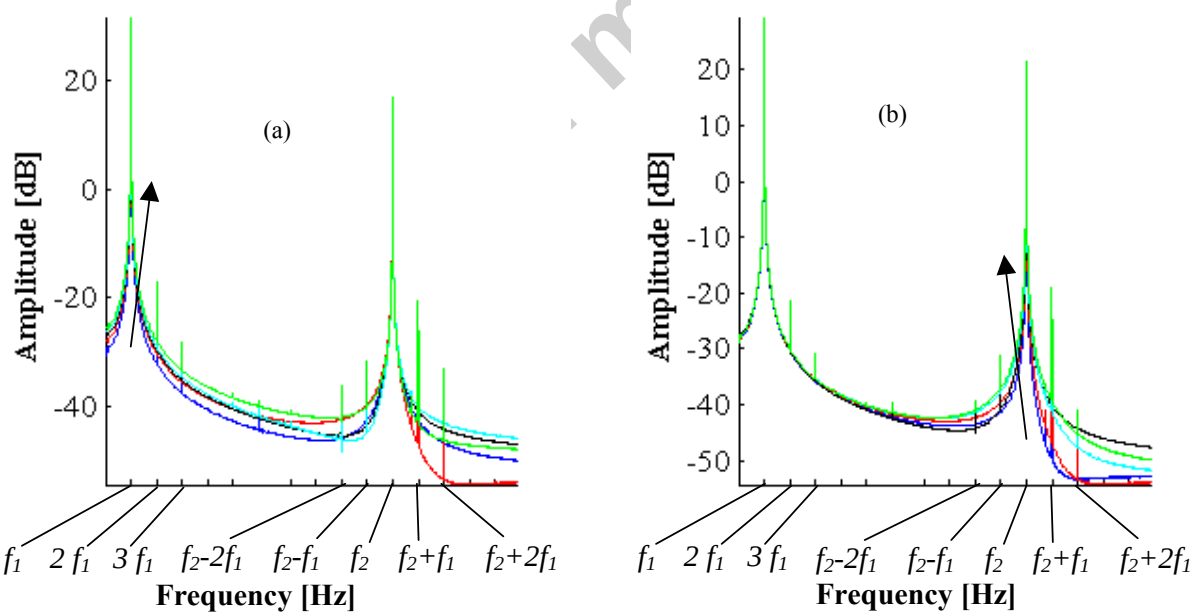

Fig. 6. Fourier spectra of accelerations measured with NWMS approach relative to the clamp condition T_1. (a) Increasing f_1 amplitude. (b) Increasing f_2 amplitude.

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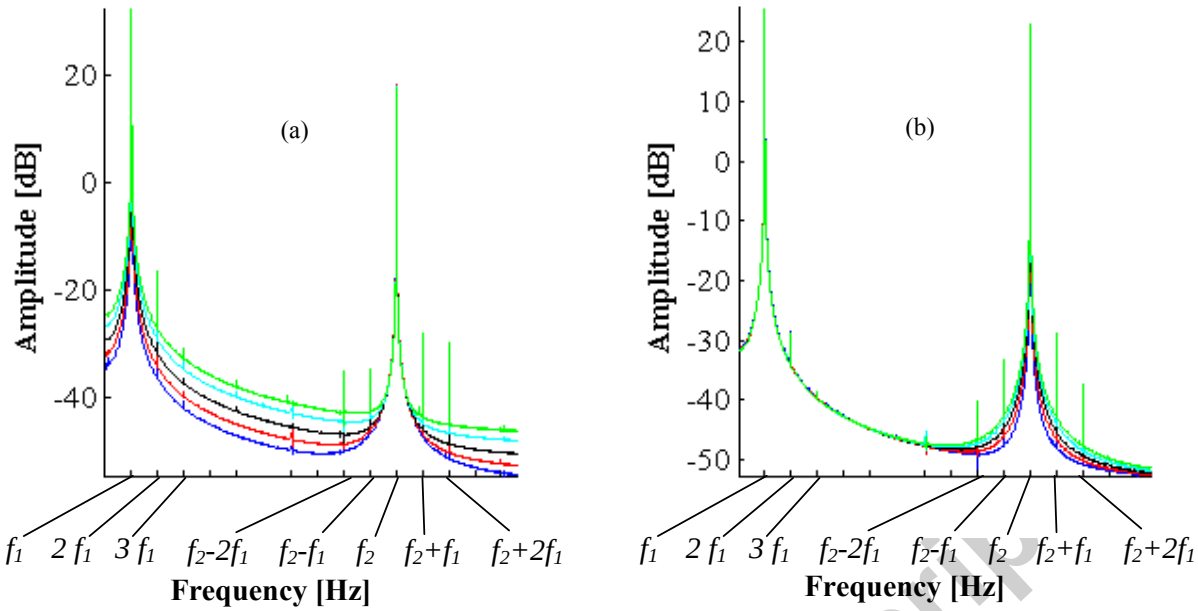

Fig. 7. Fourier spectra of accelerations measured with NWMS approach relative to the clamp condition T_2. (a) Increasing f_1 amplitude. (b) Increasing f_2 amplitude.

The results show that by varying the boundary conditions (torque value) a variation of the structural nonlinear effects was observed. In particular, a decrease of the second and third harmonic, and the first right and left sidebands was observed as shown in Fig. 8 and Fig. 9.

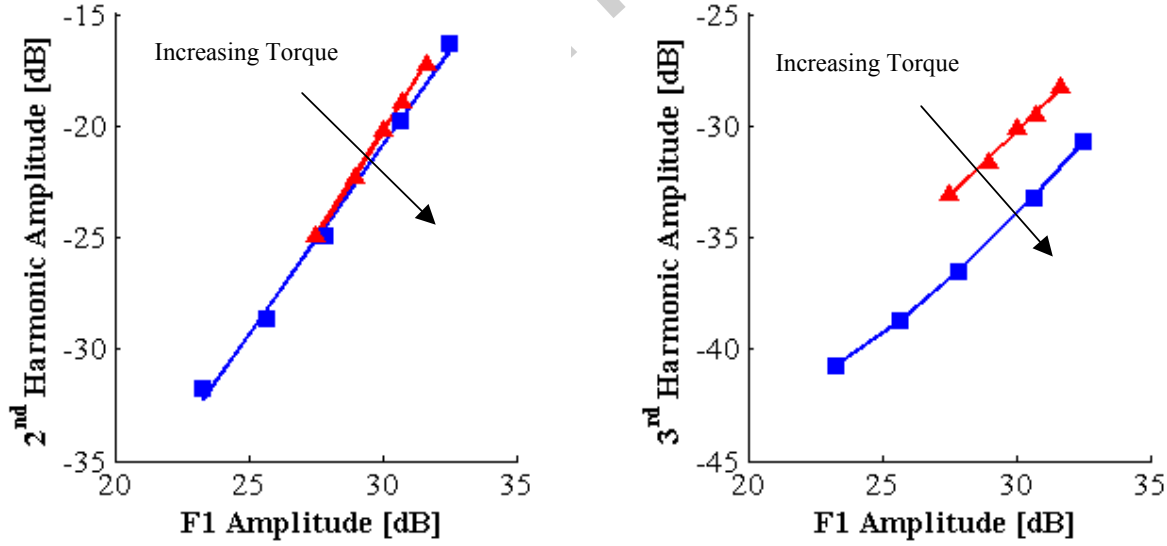

Fig. 8. Effect of the clamping torque on the observed second and third harmonics. The marker "■" indicates data for torque level T_1 and the marker "▲" indicates data for torque level T_2, where $T_1<T_2$.

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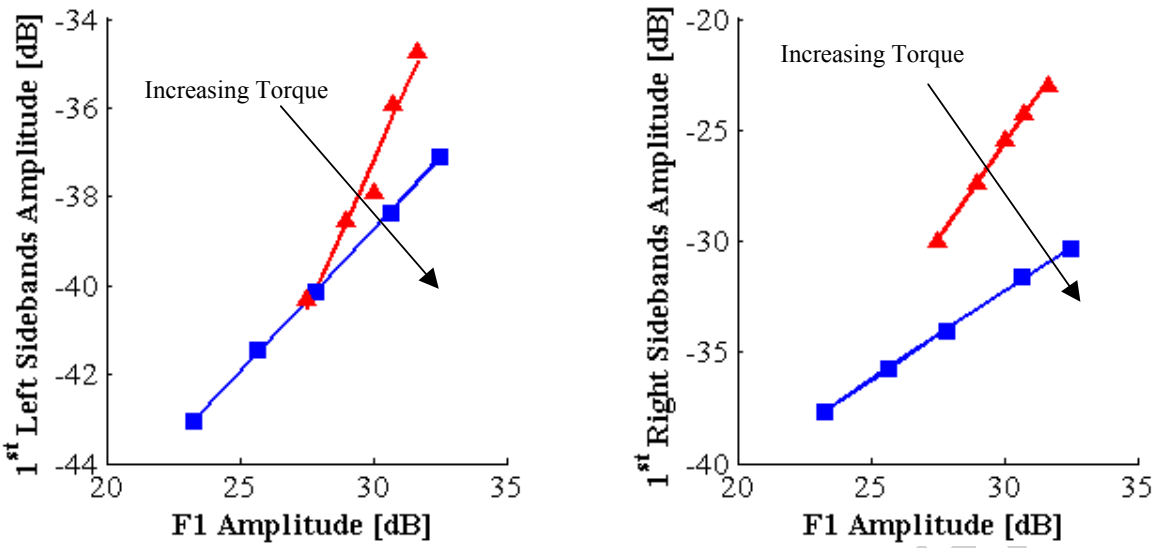

Fig. 9. Effect of the clamping torque on the observed sidebands against F1 amplitude. The marker "■" indicates data for torque level T_1 and the marker "▲" indicates data for torque level T_2, where $T_1<T_2$.

In Fig. 10 sidebands amplitude are displayed against amplitude of f_2. Tests were conducted by varying the amplitude of frequency f_2 and keeping constant the amplitude of frequency f_1. In this case, the effect of a rising of clamp torque is a decrease of the amplitudes of non linear properties.

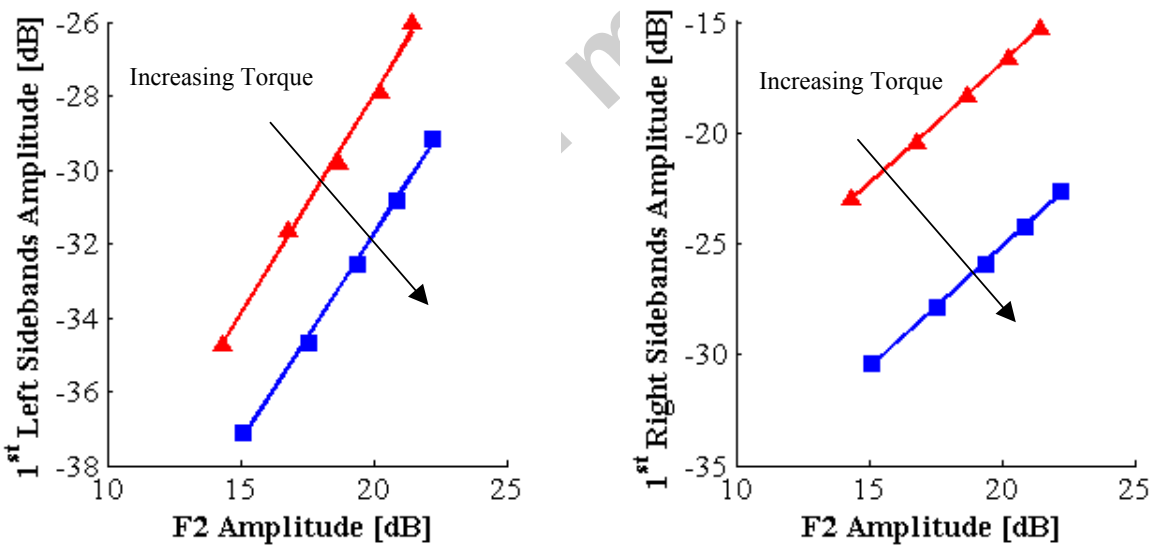

Fig. 10. Effect of the clamping torque on the observed sidebands against F2 amplitude. The marker "■" indicates data for torque level T_1 and the marker "▲" indicates data for torque level T_2, where $T_1<T_2$.

The results of these tests show some of the limitations of the NDT based on the monitoring the non-linear elastic effects. Non-classical nonlinear effects can also be generated also by the presence of contact regions, i.e. boundary conditions. There is, therefore, the need to optimise the NEWS methods and to further study these effects with other geometrical configurations, for example structures in pure contact (kissing bonds, joints etc…), and to develop methods to discern the non-classical nonlinear effects caused by geometrical configurations from that generated by the presence of impact damage.

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Conclusion

This paper investigates the generation of nonclassical nonlinear effects due to changes in boundary conditions and analyse the limitations of NEWS techniques in detecting damage in the presence of unknown boundary conditions. In this study variable boundary conditions were studied by changing the torque of clamp system used to hold the structure examined.

Two different NEWS techniques were used and both techniques, NRUS and NWMS, highlighted the presence of nonclassical non linear features in the spectrum responses. In the first case a considerable shift of first natural mode was clearly observable in the undamaged sample.

Using NWMS, the intermodulation effects were evident, highlighted by the presence of sidebands and harmonics, induced by the boundary conditions. However, the non linear properties showed a decrease in amplitude when the clamp torque was increased.

The results of these tests demonstrate that boundary condition can cause linear material to behave in a non linear elastic manner, and therefore providing false-positive indications of damage.

The results shows that more work is needed to demonstrate the effectiveness of the NEWS methods and further research studies and methodology development are needed to discern nonlinear effects generated by contacts between mating parts from those generated by the presence of damage.

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