Nonlinear vibroacoustic wave modulations for structural damage detection: an overview

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Abstract. We present an overview of research developments related to the nonlinear vibroacoustic modulation technique used for structural damage detection. The method of interest is based on nonlinear interactions of a low-frequency pumping wave and a high-frequency probing wave. These two waves are introduced to monitored structures simultaneously. Then the presence of damage is exhibited by additional frequency components that result from nonlinear damage-wave interactions. A vast amount of research has been performed in this area over the last two decades. We aim to present the state-of-the-art of these developments. The major focus is on monitoring approaches, modeling aspects, actuation/sensing, signal processing, and application examples.

1 Introduction

Structural integrity is of major concern in virtually every engineering application. Assuring the desired performance and safe operation of engineering structures is not a trivial task. This problem is equally important for new structures as well as for existing aging infrastructure. Maintenance of structures is a critical aspect when it comes to safety considerations. Effective maintenance not only improves safety and the perception of safety, but also minimizes the cost of ownership and mitigates unnecessary repairs. It is well-known that nondestructive testing (NDT) is the field of engineering that addresses this important problem, assuring the desired level of safety.[1,2] There are numerous experimental techniques that can be used to reveal structural damage including the classical NDT methods such as: visual inspection, liquid penetrant testing, leak testing, infrared and thermal testing, x-ray radiography, electromagnetic testing, magnetic testing, ultrasonic testing, and shearography.[1–4] Current NDT techniques used for damage detection are still labor-intensive, time-consuming, and often expensive, despite numerous efforts related to automation. Moreover, NDT inspections are performed only at predefined time intervals. Such inspections are often not sufficient to capture the evolution of damage in monitored structures. In addition, the application of advanced materials and manufacturing processes raises the complexity of inspection and requires an ever increasing accuracy of detection. Structural health monitoring (SHM)—based on sensors that are integrated with structures and used to continuously assess structural health[5–8]—is an answer to this important problem. The most commonly used SHM techniques are based on guided ultrasonic waves propagating in plate-like structures, beams, and pipes.[9–12] These techniques are particularly attractive due to their ability to inspect large structural areas with a relatively small number of transducers. Scattering, attenuation, and mode conversion are the signal features commonly used for damage detection. These methods work well on the assumption that damage present in the material exhibits significant impedance contrasts that alter the linear features of propagating ultrasonic waves of any type. Wave speed alterations due to corrosion or wave attenuation due to open cracks are good examples of features revealed when the classical guided wave techniques are used. However, these features are often ambiguous and it is not clear whether the observed wave alterations result from the presence of damage or from structural features (e.g., varying thicknesses, bolts or rivets) or operational/environmental conditions. Therefore, the majority of the techniques require baseline measurements that represent undamaged conditions for reference. It is also important to note that fatigue cracks and highly branched stress corrosion cracks often produce similar wave responses that cannot be distinguished when linear ultrasonic techniques are applied. Therefore, other approaches that can reveal damage are sought. Methods based on nonlinear vibration/acoustic phenomena are of special interest, gaining an increasing attention in the scientific community.[9,13–16] This is mainly due to the fact that the nonlinear damage detection methods are usually more sensitive to detect small damage severities than their linear counterparts,[14–20] thus can nicely complement the existing linear techniques.

This paper aims at summarizing the theory and practice of the nonlinear vibroacoustic wave modulation (VAM) technique applied for structural damage detection. The intention is not only to provide an overview of various research activities but also to underline strengths and limitations of the method when applied to specific damage detection problems.

The paper is structured in the following way. Section 2 provides the theoretical background of nonlinear acoustics, focusing on the nonlinear VAM technique. Section 3 discusses selected aspects of modeling and numerical simulations that can be used to support nonlinear acoustic damage detection. Section 4 discusses the commonly used methods of excitation and sensing in experimental testing.

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Section 5 describes signal processing techniques that are used to reveal damage from nonlinear responses. Section 6 demonstrates selected application examples of the method. Finally, the paper is concluded in Sec. 7.

2 Methods

2.1 Background

Historically, the "classical" nonlinear acoustics was formed as a weak nonlinearity branch of the theory of gas dynamics and the theory of elasticity. These theories deal with homogeneous materials, where the nonlinearity of propagating waves—observed at macroscopic scale—arises from inhomogeneity and physical interactions at both microscale and mesoscale.[13,15,18] The nonlinear stress–strain relation leads to the distortion of the propagating waveform and the generation of higher harmonics in signal response spectra. In the case of wave propagation in homogenous, weakly dispersive media—when strains are typically of the order of 10^{-5} to 10^{-6}—measurable nonlinear responses develop only due to the accumulation of nonlinearity along the propagation distance. Many media and engineering materials have, however, a complex structure that includes grains, pores, cracks, and similar microscale and macroscale features that greatly enhance the observed nonlinear responses. The presence of such material discontinuities—microcracks in solids or bubbles in water—leads to the so-called "nonclassical" nonlinear phenomena that can be observed in response signals and spectra. The term "nonclassical" is used in the literature to distinguish the new techniques used for material damage characterization from the "classical" nonlinear acoustics techniques described above. The term "nonclassical" is often put in parentheses to acknowledge the fact that the underlying physics and nonlinear mechanisms that are involved have also been described in a different context and are not unique to this field of research.

Manifestations of the "nonclassical" nonlinearities that have been described in scientific literature include the generation of higher harmonics whose amplitudes do not decay as fast as in the classical case, higher harmonics of unusually high orders with a specific *sinc* modulation of their spectral amplitudes, generation of subharmonics, frequency mixing, instabilities or chaotic dynamics.[13,15,18] Nonlinear mechanisms responsible for the observed signal features include: the nonequilibrium dynamics due to the presence of soft inclusions in the hard matrix of a material,[15] hysteretic behavior of certain materials including rocks and some metals,[15] the Luxembourg–Gorky effect leading to modulation transfer,[21,22] dissipative mechanisms,[23–26] the memory effect,[24,27] and the contact acoustic nonlinearity.[28] All these described mechanisms result in considerable response signal nonlinearities that can be observed and used for damage detection.

2.2 Nonlinear Vibroacoustic Wave Modulations

There are different experimental arrangements that can be used to analyze the nonclassical nonlinearities. Many of them fall under a broad category of "pump-probe" techniques that have been long used in nonlinear acoustics.[29–31] The idea is to apply two dynamic fields—an intensive high-amplitude field to perturb the material elasticity (pump wave) and a
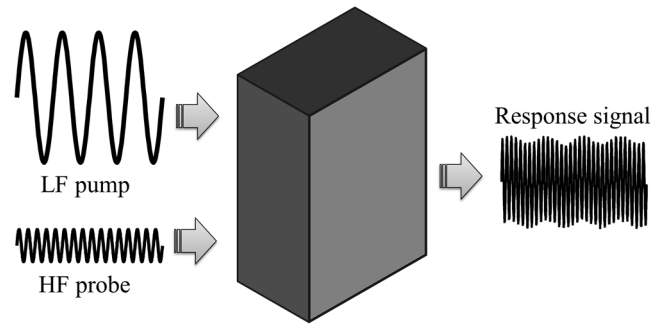
Fig. 1 The principle of the vibroacoustic wave modulation technique (VAM).

weak field to measure the induced elastic changes (probe wave). The nonlinear VAM technique that is the subject of this paper also falls into this category.

Typically, one uses a weak high-frequency (HF) ultrasonic wave as the probe and an intensive low-frequency (LF) modal/vibration excitation as the pump wave. The two waves are introduced to the structure simultaneously, as illustrated in Fig. 1. In an idealized case, when the sample is perfectly linear, the response signal spectrum exhibits only the major frequency components, i.e., the HF probe and LF pump. However, when the sample is nonlinear (e.g., due to the presence of damage), the spectrum of the response signal reveals additional frequency components such as higher harmonics and modulation sidebands around the HF probe component. Figure 2 presents real experimental responses obtained in VAM experiments for an undamaged sample [(a) and (c)] and for a damaged sample [(b) and (d)].

Other experimental scenarios are also possible including modal hammer excitation to provide the LF pump or frequency sweep excitation for the HF probe. This will be discussed in more detail in Secs. 4 and 5. Response signals acquired from VAM experiments have to be processed in order to extract damage features. Various signal processing workflows and damage indicators have been used in the literature. These developments will be discussed in detail in Sec. 5.

In the literature, the VAM technique is also referred to as the combination-frequency method,[18] nonlinear acoustic modulation method[32] or more widely as nonlinear wave modulation spectroscopy.[33]

3 Modeling

There are many underlying physical mechanisms that lead to the observed signal modulations, as mentioned already in Sec. 2, and in many cases no clear understanding of these mechanisms is known. In addition, similar nonlinear effects that are observed may be essentially caused by different nonlinear physical mechanisms. It is, therefore, very difficult to formulate and analyze models describing the VAM, as observed in experimental measurements. There are, however, many literature sources that deal with the aspects of nonlinearities involved in the VAM, both theoretically and numerically.[14,15,18,34–36]

Theoretical considerations related to nonlinear mechanisms involved in the VAM are discussed in Refs. 14, 15, 18 and more recently in Ref. 35. Specifically, Ref. 14 provides an excellent overview of the theoretical aspects of
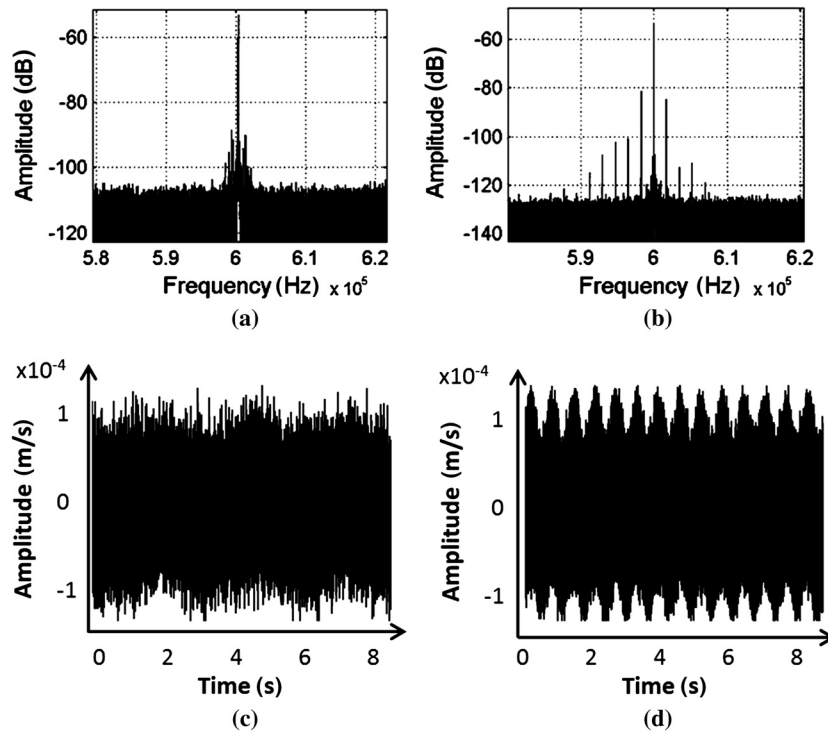
Fig. 2 (a) and (b) Examples of ultrasonic response power spectra zoomed around the high-frequency wave, and (c) and (d) the corresponding time domain signals for nonlinear acoustics test: (a) and (c) undamaged structure and (b) and (d) damaged structure.

the nonclassical nonlinearities as well as computational studies for hysteretic nonlinearities. A comprehensive review of modeling approaches used for nonlinear crack–wave interactions has been provided in Ref. 34. Various models of classical and nonclassical crack-induced elastic, thermoelastic, and dissipative nonlinearities were discussed including: classical nonlinear elasticity, bilinear stiffness, breathing cracks and clapping contacts, hysteresis, Hertzian contact, rough-surfaces contact (plastic and elastic), nonlinear dissipation, thermoelasticity, and the Luxemburg–Gorky (L–G) effect.

Arguably, the most commonly accepted explanation for the observed signal modulations in the VAM—that is used in numerical simulations—is the one arising from interactions between a discontinuity (e.g., crack or delamination) that is perturbed by the pumping wave and the traveling probing wave, as shown schematically in Fig. 3.

Both, i.e., local and nonlocal problem, formulations for continuum mechanics are applied to simulate crack–wave interactions and wave modulations, as reported in Refs. 14, 37–39.

Applications of the local interaction simulation approach (LISA) and the elastodynamic finite integration technique simulations in connection with the Preisach–Mayergoyz formalism are discussed in Ref. 14. Similar studies, making use of the LISA, are described in Ref. 38. The authors have introduced a two-step procedure for the investigation of wave modulation. First, an FE model of a rectangular plate with a centrally localized crack has been subjected to modal analysis to determine resonance frequencies and normal modes, which exhibit fundamental crack's deformations. Then the resonance vibrations observed for the crack's opening–closing mode have allowed one for indirect

introduction of the contact phenomenon into the LISA model via a periodic change of the material properties in the area of the crack. Finally, modulations regarding additional HF excitation have been observed in the model undergoing the LF crack's opening and closing.

An overview of nonlocal modeling approaches is provided in Ref. 39. The described analyses modeled with peridynamics refer to the following phenomena: reflection of Lamb waves at a crack face, higher order harmonics generations, clapping phenomenon, and wave generation during crack growth, known as acoustic emission in experimental
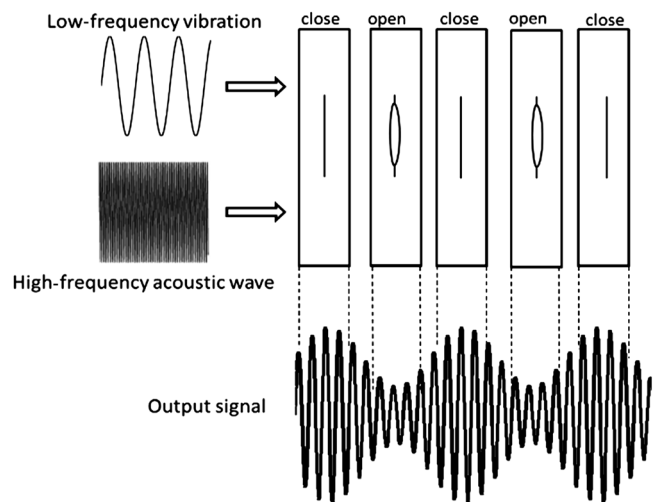
Fig. 3 Interaction between a discontinuity and traveling waves causing response signal modulation.

works. The authors in Ref. 37 presented a simulation study of the generation of frequency mixing components in a cracked aluminum plate with the use of peridynamics. The results show that the phenomena of wave interaction and modulation can be effectively simulated with the application of peridynamics. In the realm of nonlocal modeling, it should be also highlighted that the concept of long-range interactions, preferably governed by an integral-based formula, offers a more convenient technique for the introduction of any geometric discontinuities, e.g., notches. Moreover, a mesh of particles or nodes with a far distance reaction neighborhood seems a better choice for the modeling of a spontaneous crack's growths rather than any classical and explicitly structured meshes of patterns for local forces only.[40,41]

4 Sensors and Actuators

Excitation signals in VAM experiments can be provided by different means. The choice of specific actuators will be determined by measurement configurations. The most popular configurations are the vibromodulation (VM) and impact-modulation (IM) scenarios.[33,42–44] Both scenarios differ in the way in which the LF pump excitation is applied. VMs employ monoharmonic excitation of the monitored structures (as shown in Fig. 1), whereas IMs use impact excitation of the natural modes of vibration of the monitored structure. It is important to note that even in VM methods—where the LF pump can be arbitrarily selected—the LF pump is commonly chosen to correspond to one of the vibration modes in order to amplify the vibration responses. In both cases, the HF pump is applied as a single-frequency harmonic excitation. Another possibility is to utilize the L–G effect resulting in modulation transfer from an amplitude-modulated pump wave to a weaker single-frequency harmonic probe wave.[21,22,45] In this case, the LF pump is amplitude modulated with frequency Ω that should be significantly smaller than both the carrier LF and HF frequencies. The ratio between the LF pump and HF probe may be quite arbitrary. Recently, the fourth scenario has been applied. A linear frequency sweep has been used for the HF probe excitation in this scenario, as reported in Refs. 46–49. The justification for that scenario is an observation that the level of modulation sidebands depends on the frequency response function (FRF) of the sample. Thus, when the FRF is known, both—i.e., pump and probe—excitation signals could be selected to provide clear results. However, the problem is that the FRF changes when environmental or boundary conditions change. For this reason, in real engineering applications it is more robust to use broad-frequency excitation. The aspects of optimal frequency selection for both the LF pump and HF probe in VAM is currently an active area of research and one should expect to see new developments in this area in the near future.

Various actuators and sensors can be used for VAM experiments. Actuators that are frequently used for LF vibration/modal excitation include electrodynamic shakers,[25,50–53] magnetostrictive shakers,[54] instrumented modal hammers with replaceable tips (soft, medium, hard) that can modify excitation frequency bands,[42] lead zirconate titanate (PZT) transducers,[33,55] piezoceramic stack actuators,[46,56,57] cleaning ultrasonic converters,[58] lasers,[59,60] and loudspeakers.[32,61] PZT transducers are most frequently used for the HF excitation.[25,46,52,56,57] Other possibilities include ultrasonic water-coupled transducers,[54] air-coupled transducers,[32] Smart Layer® transducers,[56] microfiber composite (MFC) transducers,[62] and lasers.[59,60,63,64]

There exist multiple possibilities for response signal sensing. Predominantly, standard PZT transducers are used[33,42,43,47,50,51] followed by Smart Layer® transducers[56] and MFC transducers.[62] Sensing and exciting PZT transducers can also be integrated into VAM sensors.[65,66] Contact sensors have the advantage that they can be integrated or embedded into monitored structures to provide a means for continuous monitoring. Noncontact measurements are often performed with laser Doppler vibrometers (LDVs) or scanning laser Doppler vibrometers (SLDVs).[25,46,52,53,57] These lasers have the advantage of being very flexible in the choice of measurement locations and allow for spatial mapping of signal modulations which can be used for damage localization. LDVs and SLDVs are especially useful for laboratory experiments. Alternatively, air-coupled transducers[32] can also be used for noncontact measurements.

5 Signal Processing

In the VAM technique, measured response signals are most commonly analyzed in the frequency domain. This is a natural consequence of the damage detection principle that assumes the appearance of sideband frequency components in the response spectra under the presence of damage. Depending on the experimental configuration (i.e., the type of excitation signals), different signal processing schemes and damage indicators have been proposed.

In the case of a monoharmonic continuous LF pump and HF probe (as shown in Fig. 1), the modulation intensity coefficient is one of the most commonly used damage indicators. This coefficient is calculated as the ratio between the sum of amplitudes A_{LSB}^i and A_{RSB}^i of the i'th pair of modulation sidebands and the A_{HF} amplitude of the HF component, i.e.,

$$R = \frac{\sum_{i=1}^{n}(A_{LSB}^i + A_{RSB}^i)}{A_{HF}}. \tag{1}$$

Frequently, only the first pair or the first few pairs of sidebands are considered in computation of the R parameter. Previous studies[25,52,57] demonstrate that this parameter is a good indicator of damage presence in structures.

In other cases—where modal hammer impact is used for the LF pump excitation and tests are performed for multiple ultrasonic frequencies[42,54]—the average damage indicator is used in the form

$$R_{IM} = 20 \log_{10}\left(\frac{1}{q}\sum_{m=1}^{q}\frac{A_{m-n}+A_{m+n}}{2 \cdot A_m}\right), \tag{2}$$

where A_m is the amplitude of the ultrasonic excitation at the frequency step m, A_{m-n} and A_{m+n} are the first left and right modulation sidebands for the HF probe at the step m and n'th vibration mode, and q is the total number of HF excitation steps. The idea is that repeating the test and averaging the modulation intensity measure for multiple HF steps and different normal modes provide a more robust assessment of the damage state. This is due to the fact that the results are less affected by sample geometry, transducer positions, and the location of damage.

More recently, the authors of Ref. 46 proposed to use a frequency sweep signal for the HF probe excitation. Signal processing in this case starts with the acquired time domain response signal. Modulation in the time domain is extracted using the Hilbert transform-based amplitude demodulation and then the extracted envelope is transformed into the time–frequency domain using the short-time Fourier transform. Damage can be detected through the presence of significant energy at the harmonics of the pumping signal. Alternatively, the average amount of modulation can be determined through the Fourier transform of the extracted envelope. In addition, it has been shown that the presence of damage could be detected both through an increase in the amount of normalized modulation and without the use of historical data by utilizing generalized extreme value statistics.

The authors in Refs. 47 and 67 proposed an experimental setup with monoharmonic pump excitation and linear chirp probe excitation combined with the first spectral sideband (FSS) extraction technique. The idea is to measure the responses of the probing and pumping signals prior to the actual VAM measurement. Two separate response signals are obtained by independently applying the probing and pumping signals. Subsequently, those signals are subtracted in the time domain from the measured VAM response leaving only the spectral sideband components. The procedure has been called linear response subtraction (LRS). In addition, signal demodulation (SD) is performed to isolate only the FSS component. The complete signal processing path is, therefore, termed LRS-SD. Damage is identified by comparing the amplitudes of the FSS components extracted from the intact and damage cases. The technique can be extended to the case of multiple-pump frequencies. In this case, the LRS-SD procedure has to be performed multiple times for different pump frequencies and the result is presented in the form of a three dimensional FSS map representing probe frequency versus pump frequency versus first sideband amplitude.

A different signal processing scheme for the case of a fixed pump frequency and linear chirp probe was presented in Refs. 48, 49, and 68. The procedure is based on a wavelet transform of the acquired time domain signal to obtain the time-frequency (time–wavelet scale) representation. Subsequently, the sideband components are demodulated for each frequency by calculating the Fourier transform of the signal envelope. The end result is a frequency-amplitude representation of the demodulated sideband components. Damage is identified by comparing the sum of the demodulated sideband amplitudes with reference data for an undamaged specimen. Similar to the LRS-SD method, this technique can be applied in the case of multiple-pump frequencies. In the presented case, the authors of Ref. 48 have used a set of pump frequencies which corresponded to the modal frequencies of the sample.

Recently, VAM signals were analyzed in the time domain for detecting cracks in metallic structures[69] and delaminations in composites.[70] In both cases, the instantaneous amplitude and phase were analyzed. The study in Ref. 69 revealed that the intensity of amplitude modulation correlates far better with crack lengths than the intensity of frequency modulations. A similar result was obtained in Ref. 70 showing that increased amplitude modulation effects are measured at the damaged area, whereas there is no direct relation

between the location of the damage and the frequency modulation. The authors in Ref. 71 successfully used bispectral analysis to detect cracks in steel beams using the VAM. In addition, it has been shown that the bispectrum can be used to quantify the extent of cracking. VAM has been also used in connection with time reversal processing in order to locate sources of nonlinearity.[72,73] Most recently, VAM data has been analyzed using the cointegration technique adopted from the field of econometrics.[74]

In addition, recent research efforts have also been on extending the capabilities of VAM to localize and estimate the extent of damage. Research in this area includes the use of noncontact ultrasonic transducers to localize simulated and impact damage in a thin-polystyrene plate[32] or fatigue cracks in aluminum components.[75] In both cases, the localization of damage is obtained by scanning a certain area of the test specimen and mapping the intensity of modulation derived from the amplitudes of the sideband components. Similar approaches have been also presented using hybrid contact–noncontact systems to localize damage.[76,77] Reference 76 demonstrates the technique using a combination of contact and noncontact ultrasonic transducers to detect delamination in a carbon fiber reinforced laminate. Reference 77 describes an experimental setup based on a photoacoustic excitation of an HF probe. The test sample is excited with vibration signals generated using a fixed piezoelectric transducer and a moving intensity-modulated laser source. Signals for the mixed frequency components are captured by a moving accelerometer. A similar contact-noncontact imaging technique using fixed piezoceramic transducers for excitation and a scanning laser vibrometer for signal acquisition has been described in Ref. 78.

6 Application Examples

The VAM technique has been successfully applied to many types of materials, geometries, and damage types. Literature sources regarding this topic are very abundant and it is very hard, if not impossible, to provide a complete overview of all papers that have been published on this topic. This task is even more complicated when acknowledging the fact that papers are published in different scientific communities—including acoustics, NDT/E, SHM, materials science, geophysics, composite science, concrete science—and across many research journals. A selected number of papers that cover a wide variety of applications are presented in this section. It is clear that this list is not complete. Nevertheless, the papers that have been selected give a very good insight into the types of materials, structures, and damage types that have been analyzed with the VAM. Within this assumption, one can analyze various applications that will be classified according to the material types and damage types that have been investigated.

6.1 Metals

The first applications of the VAM for structural damage detection were related to cracks in metals. These applications include fatigue crack detection in steel,[42,46,50,55,79,80] fatigue cracks in aluminum,[25,44,47,56,58,67,81] welding cracks in steel pipes,[43,82] copper rods,[83,84] cast automotive components,[33,54,72,82,85] forged nickel alloy components,[80] diffusion bonded steel,[72] aluminum and steel pipes,[54,86] aircraft fuselage panels,[85] and railway-wheel disks.[87]
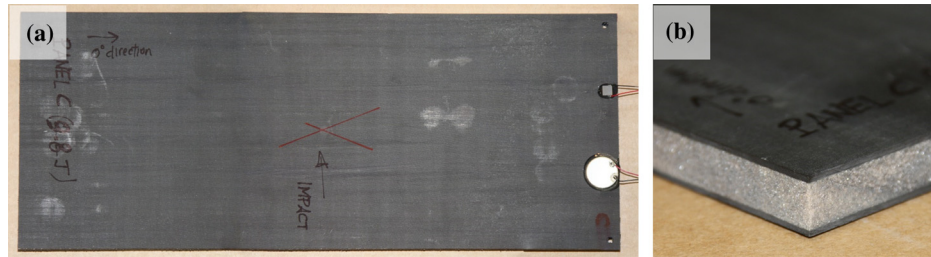
Fig. 4 Composite sandwich panel investigated with VAM—(a) top view and (b) detail of the sandwich structure (modified from Ref. 57).

6.2 Composites

More recently, the technique has been applied to detect barely visible impact damage in laminated composites[51,52,61,65,66] composite sandwich panels with a Nomex honeycomb core[55,88] and polyurethane foam core,[57] chiral panels,[53,89] cracks in wind turbine blades,[62] and composite airframe components.[82]

6.3 Other Materials

Other applications include crack detection in concrete,[82,90,91] glass,[21,72,92] sandstone rock,[18,33] Plexiglass,[33] Perspex[80] or slate tiles.[93] In addition, Refs. 19 and 72 mention successful applications of the VAM to stress-corrosion cracks in steel pipes, bonding quality assessment in titanium and thermoplastic plates used for airspace applications, cracks in aircraft steel fuse pins, cracks in combustion engine parts, damage in asphalt, cracks in polycarbonate used for aircraft fuselage, cracks in titanium alloys used in aircraft engines, titanium rotor blades, and damage in bearings caps and rings of different forms from sintered metal.

6.4 Selected Application Case

This section presents an example of damage detection application in composite sandwich panels. A detailed study on this subject is presented in Ref. 57. The test specimens used in this study were light composite sandwich panels.

The overall dimensions of the panels were $400 \times 120 \times 13.2$ mm. The face sheets were made of Seal Texipreg HS300/ET223 prepreg system, with the $[0/90_3/0]$ ply stacking sequence. The total thickness of the face sheet laminate was 1.6 mm. The core material was a closed-cell polyvinyl chloride foam DIAB Divinycell HP60. The thickness of the foam core was equal to 10 mm. A picture of the panel is shown in Fig. 4.

One of the panels was impacted in the center with the energy of 9.8 J to develop a barely visible impact damage (BVID) with an area of approximately 640 mm². The VAM tests were performed on the damaged panel and a reference healthy panel using the same experimental setup. The LF pump and the HF probe were applied by a PI Ceramic PL055.30 piezoelectric stack and PI Ceramic 15×1 mm piezoelectric disc, respectively. Both the LF and HF transducers were driven by an Agilent 33522A arbitrary signal generator through an EC Systems PAQG amplifier. The response signal was acquired using a Polytec PSV400 SLDV. The LF pump frequency was equal to the first bending mode of the panel ($\sim$700 Hz) and the HF probe was arbitrarily selected at 40 kHz. LF excitation was in the range from 10 to 70 V_{p-p} with an increment of 10 V_{p-p}.

Results of the experiments are presented in Fig. 5. The measured response spectrum of the undamaged panel in Fig. 5(a) shows no modulation sidebands around the HF probe component, whereas the spectrum in Fig. 5(b)
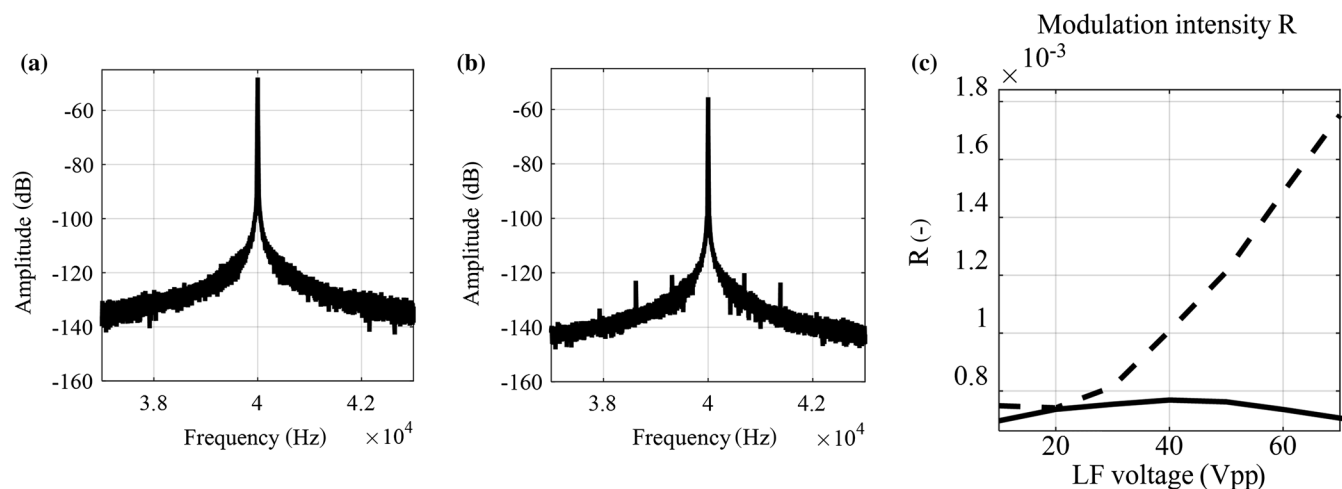
Fig. 5 Results of the VAM test on composite sandwich panels: (a) response spectrum of the undamaged panel, (b) response spectrum of the damaged panel, (c) modulation intensity coefficient for different LF drive levels: solid line represents undamaged panel and dashed line represents damaged panel (modified from Ref. 57).

measured for the damaged specimen clearly shows the modulation sidebands. Finally, Fig. 5(c) presents the modulation intensity coefficient versus driving pump voltage, calculated according to Eq. (1), for both the damaged (dashed line) and undamaged (solid line) panels. The results show that the damaged and undamaged conditions can be clearly distinguished. It is important to note that in industrial applications, the experimental setup for the VAM test could be simplified by replacing the SLDV with a piezoceramic transducer, or an integrated VAM transducer as mentioned in Sec. 4, to obtain an efficient health monitoring system. The purpose for discussing this example is to show that the application of VAM is fairly straightforward as there is no need for highly specialized or custom test equipment or signal processing techniques.

Despite the many successful applications mentioned above, the VAM technique has certain drawbacks. One of the most important is the influence of intrinsic nonlinearities (e.g., related to boundary conditions) on the observed signal modulations. This problem has been mentioned in many studies and analyzed in detail in Refs. 45 and 94. Results presented in those studies confirm that the observed nonlinear effects depend on boundary conditions to the point where resonance shifts, higher harmonics, and modulation sidebands may be observed even in undamaged samples. Another problem, particularly relevant for SHM applications with integrated or embedded transducers is related to transducer faults. This is very important as a transducer fault may result in false-positive indications (i.e., damage is detected when none is present) or false-negative (i.e., damage is not detected when it is present) with both scenarios having potentially dramatic consequences. This problem has been extensively discussed in the SHM community.[95,96]

7 Summary and Final Conclusions

The paper presented the state-of-the-art overview of the non-linear VAM technique applied for damage detection. Due to the increased interest in the application of nonlinear techniques for damage detection, which has been observed over the last twenty years, literature sources regarding this topic are very abundant. It is, therefore, very difficult to provide a complete review of all papers that have been published on this topic. Nevertheless, the papers that have been selected provide a good overview of the theory and applications of the VAM.

The VAM technique belongs to the group of nonlinear acoustics approaches and provides the level 1 SHM capability, i.e., damage detection. That is, it can detect the presence of damage in the structure and can be used for continuous monitoring. In addition, the hardware setup necessary to implement the technique is fairly simple and, in principle, requires only three transducers—one for LF pump excitation, one for HF probe excitation, and one for signal acquisition. The three transducers can be permanently mounted on the structure or integrated in the form of a single VAM sensor. Much progress has been made over the last 20 years regarding transducer development, signal processing techniques, and the theoretical aspects of the VAM. However, the technique still faces certain challenges. One of the most important is the influence of the intrinsic nonlinearities on the observed nonlinear responses. This problem has been discussed in the literature, but more research work is

necessary to account for it before practical engineering applications become possible.

Currently, research work is underway to extend the capabilities of the VAM and test it in industrial applications. One of the extensions is to provide damage localization and size estimation based on the VAM responses. Other active research topics include signal processing techniques, numerical modeling and new excitation types.

The potential of nonlinear damage detection techniques, including VAM, is very large. The maturity of the technology and current research efforts in this area give hope for practical engineering applications in structural damage detection and monitoring in the near future.

References

1. P. O. Moore, Ed., "Nondestructive testing handbook," Vol. 10, in *Overview*, 3rd ed., American Society for Nondestructive Testing, Columbus, OH (2012).
2. C. Hellier, *Handbook of Nondestructive Evaluation*, 2nd ed., McGraw Hill Professional, New York (2012).
3. J. Krautkramer and H. Krautkramer, *Ultrasonic Testing of Materials*, 4th ed., Springer-Verlag, New York (1990).
4. J. E. Masters, Ed., *Damage Detection in Composite Materials*, American Society for Testing and Materials, Philadelphia, ASTM STP 1128 (1992).
5. A. Rytter, "Vibration based inspection of civil engineering structures," PhD Dissertation, Department of Building Technology and Structural Engineering, Aalborg University, Denmark (1993).
6. W. J. Staszewski, C. Boller, and G. R. Tomlinson, Eds., *Health Monitoring of Aerospace Structures*, Wiley, Chichester (2004).
7. D. Balageas, *Structural Health Monitoring*, Wiley-ISTE, London (2006).
8. C. Boller, F.-K. Chang, and Y. Fujino, *Encyclopedia of Structural Health Monitoring*, Wiley, Chichester (2009).
9. T. Stepinski, T. Uhl, and W. J. Staszewski, Eds., *Advanced Structural Damage Detection: From Theory to Engineering Applications*, Wiley, Chichester (2013).
10. W. J. Staszewski, "Structural health monitoring using guided ultrasonic waves," in *Advances in Smart Technologies in Structural Engineering*, J. Holnicki-Szulc and C. A. M. Soares, Eds., Springer Science & Business Media, Heidelberg (2004).
11. J. L. Rose, "A baseline and vision of ultrasonic guided wave inspection potential," *J. Pressure Vessel Technol.* **124**(3), 273 (2002).
12. V. Giurgiutiu, *Structural Health Monitoring with Piezoelectric Wafer Active Sensors*, Elsevier Science, Burlington (2008).
13. M. F. Hamilton and D. T. Blackstock, *Nonlinear Acoustics*, Academic Press, San Diego (1998).
14. P. P. Delsanto, *Universality of Nonclassical Nonlinearity: Applications to Non-destructive Evaluations and Ultrasonics*, Springer, New York (2006).
15. R. A. Guyer and P. A. Johnson, *Nonlinear Mesoscopic Elasticity: The Complex Behaviour of Rocks, Soil, Concrete*, 1st ed., Wiley-VCH, Weinheim (2009).
16. R. Guyer and P. Johnson, "Nonlinear mesoscopic elasticity: evidence for a new class of materials," *Phys. Today* **52**(4), 30–36 (1999).
17. P. B. Nagy, "Fatigue damage assessment by nonlinear ultrasonic materials characterization," *Ultrasonics* **36**, 375–381 (1998).
18. L. Ostrovsky and P. Johnson, "Dynamic nonlinear elasticity in geomaterials," *Riv. Nuovo Cimento* **24**(7), 1–46 (2001).
19. P. A. Johnson, "The new wave in acoustic testing," in *Materials World*, pp. 544–546 (1999).
20. V. Y. Zaitsev et al., "Nonlinear interaction of acoustical waves due to cracks and its possible usage for cracks detection," *J. Vib. Control* **1**(3), 335–344 (1995).
21. V. Y. Zaitsev, V. Gusev, and B. Castagnède, "Observation of the 'Luxemburg-Gorky effect' for elastic waves," *Ultrasonics* **40**(1–8), 627–631 (2002).
22. V. Y. Zaitsev, V. Gusev, and B. Castagnède, "Luxemburg-Gorky effect retooled for elastic waves: a mechanism and experimental evidence," *Phys. Rev. Lett.* **89**(10), 2–5 (2002).
23. V. Y. Zaitsev and P. Sas, "Nonlinear response of a weakly damaged metal sample: a dissipative modulation mechanism of vibro-acoustic interaction," *J. Vib. Control* **6**(6), 803–822 (2000).

24. V. Y. Zaitsev, V. Gusev, and B. Castagnede, "Thermoelastic mechanism for logarithmic slow dynamics and memory in elastic wave interactions with individual cracks," *Phys. Rev. Lett.* **90**(7) (2003).
25. A. Klepka et al., "Nonlinear acoustics for fatigue crack detection–experimental investigations of vibro-acoustic wave modulations," *Struct. Health Monit.* **11**(2), 197–211 (2012).
26. L. Pieczonka, W. J. Staszewski, and T. Uhl, "Investigation of nonlinear vibro-acoustic wave modulation mechanisms in composite laminates," *Key Eng. Mater.* **569–570**, 96–102 (2013).
27. I. Y. Solodov and B. Korshak, "Instability, chaos, and 'memory' in acoustic-wave–crack interaction," *Phys. Rev. Lett.* **88**(1), 2001–2003 (2001).
28. I. Y. Solodov, N. Krohn, and G. Busse, "CAN: an example of nonclassical acoustic nonlinearity in solids," *Ultrasonics* **40**, 621–625 (2002).
29. U. Ingard and D. C. Pridmore-Brown, "Scattering of sound by sound," *J. Acoust. Soc. Am.* **28**(3), 367–369 (1956).
30. P. J. Westervelt, "Scattering of sound by sound," *J. Acoust. Soc. Am.* **29**(8), 934–935 (1957).
31. A. Ostrovsky, S. N. Gurbatov, and A. N. Didenkulov, "Nonlinear acoustics in Nizhni Novgorod (a review)," *Acoust. Phys.* **51**(2), 114 (2005).
32. E. M. Ballad et al., "Nonlinear modulation technique for NDE with air-coupled ultrasound," *Ultrasonics* **42**(1–9), 1031–1036 (2004).
33. K. E. A. Van Den Abeele, P. A. Johnson, and A. Sutin, "Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, part I: nonlinear wave modulation spectroscopy (NWMS)," *Res. Nondestr. Eval.* **12**, 17–30 (2000).
34. D. Broda et al., "Modelling of nonlinear crack–wave interactions for damage detection based on ultrasound—a review," *J. Sound Vib.* **333**(4), 1097–1118 (2014).
35. J. Kober and Z. Prevorovsky, "Theoretical investigation of nonlinear ultrasonic wave modulation spectroscopy at crack interface," *NDT E Int.* **61**, 10–15 (2014).
36. M. Scalerandi et al., "Non-linear techniques for ultrasonic micro-damage diagnostics: a simulation approach," in *AIP Conf. Proc.*, Vol. 509, pp. 1393–1399 (2000).
37. A. Martowicz et al., "Vibro-acoustic wave interaction in cracked plate modeled with peridynamics," in *11th World Congress on Computational Mechanics (WCCM XI)*, pp. 1–2 (2014).
38. A. Martowicz et al., "Modelling of nonlinear vibro-acoustic wave interaction in cracked aluminium plates using local interaction simulation approach," in *Proc. of ECCOMAS 2012*, Vienna, Austria, (September 10–14 2012).
39. A. Martowicz et al., "Non-local modeling and simulation of wave propagation and crack growth," in *40th Annual Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 33A, pp. 513–520, AIP Publishing (2014).
40. E. Madenci and E. Oterkus, *Peridynamic Theory and its Applications*, Springer, New York (2014).
41. W. Hu, Y. D. Ha, and F. Bobaru, "Peridynamic model for dynamic fracture in unidirectional fiber-reinforced composites," *Comp. Methods Appl. Mech. Eng.* **217–220**, 247–261 (2012).
42. D. M. Donskoy, A. M. Sutin, and A. Ekimov, "Nonlinear acoustic interaction on contact interfaces and its use for nondestructive testing," *NDT E Int.* **34**(4), 231–238 (2001).
43. D. M. Donskoy and A. M. Sutin, "Vibro-acoustic modulation non-destructive evaluation technique," *J. Intell. Mater. Syst. Struct.* **9**(9), 765–771 (1998).
44. M. Ryles et al., "Comparative study of nonlinear acoustic and Lamb wave techniques for fatigue crack detection in metallic structures," *Fatigue Fract. Eng. Mater. Struct.* **31**(8), 674–683 (2008).
45. F. Aymerich and W. J. Staszewski, "Experimental study of impact-damage detection in composite laminates using a cross-modulation vibro-acoustic technique," *Struct. Health Monit.* **9**(6), 541–553 (2010).
46. C. Yoder and D. E. Adams, "Vibro-acoustic modulation utilizing a swept probing signal for robust crack detection," *Struct. Health Monit.* **9**(3), 257–267 (2010).
47. H. Sohn et al., "Nonlinear ultrasonic wave modulation for online fatigue crack detection," *J. Sound Vib.* **333**(5), 1473–1484 (2013).
48. A. Frau et al., "Probing wave frequency selection for the nonlinear vibro-acoustic wave modulation tests," in *AIAS–Associazione Italiana per l'Analisi delle Sollecitazioni, 43° Convegno Nazionale*, Bologna, pp. 9–12 (2014).
49. L. Pieczonka et al., "Optimal selection of parameters for impact damage detection in composites based on nonlinear vibro-acoustics modulations," in *ECCM16–16th European Conf. On Composite Materials*, Seville, (22–26 June 2014).
50. P. Morbidini, P. Duffour, and P. Cawley, "Vibro-acoustic modulation NDE technique. Part 2: experimental study," *Rev. Quant. Nondestr. Eval.* **24**, 616–624 (2005).
51. F. Aymerich and W. J. Staszewski, "Impact damage detection in composite laminates using nonlinear acoustics," *Composites Part A* **41**(9), 1084–1092 (2010).
52. A. Klepka et al., "Impact damage detection in laminated composites by non-linear vibro-acoustic wave modulations," *Composites Part B* **65**, 99–108 (2014).
53. I. Klepka et al., "Impact damage detection in composite chiral sandwich panels using nonlinear vibro-acoustic modulations," *Smart Mater. Struct.* **22**(8), 084011 (2013).
54. D. Donskoy et al., "N-SCAN ®: new vibro-modulation system for detection and monitoring of cracks and other contact-type defects," *Proc. SPIE* **5057**, 400–409 (2003).
55. M. Meo and G. Zumpano, "Nonlinear elastic wave spectroscopy identification of impact damage on a sandwich plate," *Compos. Struct.* **71**(3–4), 469–474 (2005).
56. Z. Parsons and W. J. Staszewski, "Nonlinear acoustics with low-profile piezoceramic excitation for crack detection in metallic structures," *Smart Mater. Struct.* **15**, 1110–1118 (2006).
57. L. Pieczonka et al., "Impact damage detection in light composite sandwich panels using piezo-based nonlinear vibro-acoustic modulations," *Smart Mater. Struct.* **23**(10), 105021 (2014).
58. L. Straka et al., "Detection of structural damage of aluminum alloy 6082 using elastic wave modulation spectroscopy," *NDT E Int.* **41**(7), 554–563 (2008).
59. S. Mezil et al., "Two dimensional nonlinear frequency-mixing photo-acoustic imaging of a crack and observation of crack phantoms," *J. Appl. Phys.* **114**(17), 174901 (2013).
60. N. Chigarev et al., "Nonlinear frequency-mixing photoacoustic imaging of a crack," *J. Appl. Phys.* **106**, 036101 (2009).
61. U. Polimeno and M. Meo, "Detecting barely visible impact damage detection on aircraft composites structures," *Compos. Struct.* **91**(4), 398–402 (2009).
62. S. Kim et al., "Crack detection technique for operating wind turbine blades using vibro-acoustic modulation," *Struct. Health Monit.* **13**(6), 660–670 (2014).
63. J. Zakrzewski et al., "Combined photoacoustic–acoustic technique for crack imaging," *Int. J. Thermophys.* **31**(1), 199–207 (2010).
64. P. Liu et al., "Noncontact detection of fatigue cracks by laser nonlinear wave modulation spectroscopy (LNWMS)," *NDT E Int.* **66**, 106–116 (2014).
65. N. A. Chrysochoidis, A. K. Barouni, and D. A. Saravanos, "Delamination detection in composites using wave modulation spectroscopy with a novel active nonlinear acousto-ultrasonic piezoelectric sensor," *J. Intell. Mater. Syst. Struct.* **22**(18), 2193–2206 (2011).
66. N. A. Chrysochoidis, T. T. Assimakopoulou, and D. A. Saravanos, "Nonlinear wave structural health monitoring method using an active nonlinear piezoceramic sensor for matrix cracking detection in composites," *J. Intell. Mater. Syst. Struct.*, 1–13 (2014).
67. H. J. Lim et al., "Reference-free fatigue crack detection using nonlinear wave modulation," in *Int. Workshop on Structural Health Monitoring* (2013).
68. A. Klepka et al., "Non-linear vibro-acoustic wave modulations–analysis of different types of low-frequency excitation," *Key Eng. Mater.* **569–570**, 924–931 (2013).
69. H. F. Hu et al., "Crack detection using nonlinear acoustics and piezoceramic transducers—instantaneous amplitude and frequency analysis," *Smart Mater. Struct.* **19**(6), 065017 (2010).
70. T. H. Ooijevaar et al., "Vibro-acoustic modulation based damage identification in a composite skin-stiffener structure," in *7th European Workshop on Structural Health Monitoring*, pp. 544–551 (2014).
71. A. J. Hillis et al., "Global crack detection using bispectral analysis," *Proc. R. Soc. A* **462**, 1515–1530 (2006).
72. A. M. Sutin and P. Johnson, "Nonlinear elastic wave NDE II. Nonlinear wave modulation spectroscopy and nonlinear time reversed acoustics," in *AIP Conf. Proc.*, Vol. 760, No. 1, p. 385, IOP Institute of Physics Publishing (2005).
73. T. J. Ulrich et al., "Time reversal and non-linear elastic wave spectroscopy (TR NEWS) techniques," *Int. J. Non Linear Mech.* **43**(3), 209–216 (2008).
74. B. Dao et al., "Impact Damage Detection in Composites using Nonlinear Vibro-Acoustic Wave Modulations and Cointegration Analysis," *11th European Conference on Non-Destructive Testing (ECNDT 2014)*, October 6–10, 2014, Prague, Czech Republic.
75. H. J. Lim et al., "Noncontact fatigue crack visualization using nonlinear ultrasonic modulation," *NDT E Int.* **73**, 8–14 (2015).
76. A. Hedberg et al., "Non-contact nonlinear ultrasound scan of a CFRP plate with manufactured damages," in *Int. Workshop on Structural Health Monitoring*, Stanford (2013).
77. J. Zakrzewski et al., "Combined photoacoustic–acoustic technique for crack imaging," *Int. J. Thermophys.* **31**(1), 199–207 (2010).
78. L. Pieczonka et al., "Impact damage imaging in composites using nonlinear vibro-acoustic wave modulations," *J. Vib. Control* (2015), submitted.
79. P. Duffour, M. Morbidini, and P. Cawley, "A study of the vibro-acoustic modulation technique for the detection of cracks in metals," *J. Acoust. Soc. Am.* **119**(3), 1463 (2006).
80. P. Duffour, M. Morbidini, and P. Cawley, "Comparison between a type of vibro-acoustic modulation and damping measurement as NDT techniques," *NDT E Int.* **39**(2), 123–131 (2006).
81. T. C. Tszeng, "Modulation spectroscopy of acoustic waves in solids containing contact-type cracks," *J. Vib. Acoust.* **135**(6), 064504 (2013).

82. A. Zagrai, D. Donskoy, and J. Lottiaux, "N-Scan®: new vibro-modulation system for crack detection, monitoring and characterization," in *AIP Conf. Proc.*, Vol. 700, No. 2004, pp. 1414–1421 (2004).

83. V. Zaitsev et al., "Micro-damage detection using a modulation technique based on dissipative nonlinear effects," in *Forum Acousticum*, Sevilla (2002).

84. V. Zaitsev and P. Sas, "Dissipation in microinhomoeneous solids: inherent amplityde-dependent loss of a non-hysteretic and non-frictional type," in *Acustica-Acta Acustica*, Vol. 86, pp. 429–445 (2000).

85. A. Zagrai et al., "Micro- and macroscale damage detection using the nonlinear acoustic vibro-modulation technique," *Res. Nondestr. Eval.* **19**(2), 104–128 (2008).

86. J. Jiao et al., "Vibro-acoustic modulation technique for micro-crack detection in pipeline," *Proc. SPIE* **8321**, 83213X (2011).

87. V. Y. Zaitsev, L. A. Matveev, and A. L. Matveyev, "Elastic-wave modulation approach to crack detection: comparison of conventional modulation and higher-order interactions," *NDT E Int.* **44**(1), 21–31, Elsevier (2011).

88. G. Zumpano and M. Meo, "Damage detection in an aircraft foam sandwich panel using nonlinear elastic wave spectroscopy," *Comput. Struct.* **86**(3–5), 483–490 (2008).

89. A. Klepka et al., "Impact damage detection in composite chiral sandwich panels," *Key Eng. Mater.* **518**, 160–167 (2012).

90. A. Payan, V. Garnier, and J. Moysan, "Potential of nonlinear ultrasonic indicators for nondestructive testing of concrete," *Adv. Civ. Eng.* 1–8 **2010** (2010).

91. V. Garnier et al., "Acoustic techniques for concrete evaluation: improvements, comparisons and consistency," *Constr. Build. Mater.* **43**, 598–613 (2013).

92. B. Jenal and W. J. Staszewski, "Crack detection in glass plates using nonlinear acoustics with low-profile piezoceramic transducers," *Proc. SPIE* **7650**, 765030 (2010).

93. K. Van Den Abeele et al., "Micro-damage diagnostics using nonlinear elastic wave spectroscopy (NEWS)," *NDT E Int.* **34**, 239–248 (2001).

94. U. Polimeno and M. Meo, "Understanding the effect of boundary conditions on damage identification process when using non-linear elastic wave spectroscopy methods," *Int. J. Non Linear Mech.* **43**(3), 187–193 (2008).

95. M. I. Friswell and D. J. Inman, "Sensor validation for smart structures," *J. Intell. Mater. Syst. Struct.* **10**(12), 973–982 (1999).

96. M. Abdelghani and M. I. Friswell, "Sensor validation for structural systems with multiplicative sensor faults," *Mech. Syst. Signal Process.* **21**(1), 270–279 (2007).

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