Journal of Applied Physics | TUTORIAL | scitation.org/journal/jap

Applications of non-linear acoustics for quality control and material characterization

Cite as: J. Appl. Phys. **132**, 161101 (2022); doi: 10.1063/5.0106143
Submitted: 27 June 2022 · Accepted: 25 September 2022 ·
Published Online: 27 October 2022

View Online Export Citation CrossMark

Roman Gr. Maev and Fedar Seviaryn[a)]

AFFILIATIONS

Institute for Diagnostic Imaging Research, University of Windsor, Windsor, Ontario N9A 5R5, Canada

Note: This paper is part of the Special Topic on: Non-Invasive and Non-Destructive Methods and Applications Part II.

[a)]**Author to whom correspondence should be addressed:** seviazy@uwindsor.ca

ABSTRACT

For several decades, nonlinear acoustic methods have been used for material characterization, quality control, and biomedical diagnostics. This approach is based on a second or higher-order phenomenon. Most nondestructive evaluation tasks employ conventional first-order ultrasonic techniques. Utilizing a nonlinear regime may bring new essential information and improve the characterization of materials with defects or flaws that are challenging to detect using traditional acoustical methods. Such defects inexhaustibly include thin cracks and dislocations through which sound passes without reflection; filled cracks or glue layers with acoustical contact between surfaces, voids, and agglomerations thereof with a dimension less than the wavelength; inclusions with a subtle acoustical difference from surrounding media; and multilayer structures with various boundary conditions between layers. For such cases, defects can be detected, visualized, and evaluated using a nonlinear reflection effect. This effect accompanies a typical sound wave reflection at interfaces between media, producing reflected and refracted waves. In the nonlinear regime, these waves have components with double frequency. The nonlinear properties of both media determine the wave amplitude. The nature of the evaluated medium determines the type and number of parameters that describe the nonlinear properties. These parameters' magnitude and spatial distribution provide valuable information about the material properties and object structure. Inspection instruments that utilize the effect of nonlinear reflection can be effective tools for quality control.

INTRODUCTION

For decades, acoustic methods have been widely used to detect and visualize flaws as well as measure local parameters in various materials. The substantial development of conventional techniques and their adaptation for multiple uses results from significant industrial demand, making ultrasonic inspection an essential and valuable part of the manufacturing process. At the same time, most ultrasonic techniques are based on measuring the bulk amplitude of reflected or scattered acoustic waves. This approach has significant limitations regarding poorly reflecting flaws, e.g., weak bonds, microcracks, or closed cracks.

The majority of acoustic phenomena employed in nondestructive evaluation (NDE) are associated with linear elastic properties of materials. The ultrasonic response of a specimen and the output signal amplitude are proportional to the amplitude of the initial wave. This linear dependence gets distorted for the high-level ultrasonic wave or materials with specific properties, and consequently, nonlinear effects may appear, e.g., amplitude-dependent wave propagation velocity, waveform distortion, higher harmonics generation, acoustic rectification of the input signal, sum and difference frequency generation for multiple input signals, acoustic streaming, self-focusing, etc. These phenomena can be used to obtain additional information about the specimen's structure and material properties. Thus, nonlinear acoustics has significant potential in nondestructive testing (NDT), as the emergence of nonlinear properties often relates closely to the nature and amount of defects in the inspected material. Over the last decade, nonlinear acoustic NDE has attracted considerable interest due to its practical importance. Nonlinear acoustic techniques have proven useful for many applications, e.g., the measurements of adhesion strength in layered structures, nondestructive detection of fractured defects (e.g., in crystals, ceramics, carbon electrodes, and concrete structures), and nondestructive detection of fatigue cracks in metals (e.g., steels, titanium, and aluminum alloys).[1–6] Nonlinear acoustic methods have also been successfully used to detect early stage deterioration damage and other defects that are generally undetectable with conventional NDE techniques.[7–11]

According to the linear theory of acoustic wave propagation, Hooke's law describes the stress-strain relation as linear.[12] In other words, coefficients of proportionality between stress and strain components, i.e., elastic constants in a medium, are constant. Density changes caused by the wave are neglectably small, and correspondingly, its velocity should be constant and independent from its amplitude. Thus, a monochromatic acoustic wave is not distorted during its propagation in a medium, although its amplitude is reduced due to dissipation and diffraction. Accordingly, two elastic waves propagating through the same volume of materials do not affect each other and do not interact in the linear theory (superposition principle). This approach is valid for low-amplitude waves which cause negligible local changes in strain, pressure, temperature, and density. As wave amplitude increases, these conditions weaken, and amplitude-dependent (nonlinear) effects become more noticeable. In continuous media, the linear behavior of acoustic waves is determined by second-order elastic constants. In contrast, nonlinear phenomena can be described by introducing higher-order elastic constants. A classic example is the profile distortion of the acoustic wave. In a number of nonlinear media, including water, the peaks of a particle velocity profile travel faster than the troughs. Consequently, an initially harmonic acoustic wave obtains a saw-tooth-like profile of particle velocity, with distance. With thermal and viscous losses taken into account, such a process can eventually result in the formation of a shock wavefront. In the frequency domain, the waveform distortion is represented by the generation of higher harmonics. That is, nonlinearity results in an acoustic energy spectral redistribution—the transfer from the fundamental frequency wave to higher harmonics. Detection and analysis of these harmonics are one of the fundamental approaches for nonlinear acoustic material characterization.

A variety of parameters are usually defined to quantitatively assess acoustic nonlinearity, including the nonlinear coefficients βn of the higher-order terms in the local speed variation of particle velocity (or strain) in the wave, the nonlinearity parameter B/A representing the normalized coefficient of the quadratic term in the material equation of state, and the acoustoelastic constant describing the relation between the acoustic wave velocity and the stress (strain) applied to a solid material.[7] They all depend solely on the linear and nonlinear elastic parameters of the material. The nonlinear coefficients βn and acoustoelastic constants are usually applied to characterize solid media, while the nonlinearity parameter B/A is widely used in the case of liquid media and biological soft tissues.[13] The second-order nonlinear coefficients (βn and B/A) are primarily involved in characterizing the elastic nonlinearity of liquids and flawless solids. In special cases of nonclassical solid materials, the higher-order nonlinear effects could evolve dramatically, and the higher-order nonlinear coefficients βn should also be considered.

Nonlinear parameters provide additional valuable information that cannot be obtained by conventional linear acoustic methods. Traditional acoustic nonlinearity is a direct measure of the material anharmonicity which originates in the nonlinear behavior of the intermolecular lattice forces. Nonlinear elastic properties of solids with micro- and macro-defects (scaled from dislocations to volume inclusions) or having structural disruptions may be described by the introduction of specific types of acoustic nonlinearity.[14,15] This can be used as a measure of the "defectiveness" of a material and structural integrity of the samples during dynamic tensile tests. Despite the variance of nonlinear mechanisms, a quantitative assessment of elastic nonlinearity of any scale and type can be represented by values of classic nonlinear coefficients. Amplitudes of the generated higher harmonics are proportional to these coefficients.

Nonlinear acoustic methods can be especially useful for the characterization and location of fractured inhomogeneities and defects in solid materials. The key characteristic element of such inhomogeneous inclusions (pores, cracks, boundaries between grains, structural frames, etc.,) is an internal interface that separates the intact material and inclusion. This interface can be either free (large pores and opened cracks), partially clamped ("clapping" contact of closed cracks and zero-volume unbonds), or ideally bonded.[16] There is a specific type of boundary acoustic nonlinearity even for the ideally bonded interface.[17] The acoustic wave passing through the interface can result in strong nonlinear phenomena accompanied by efficient reflected and transmitted harmonic generation. All participating waves contribute to the interface's acoustic nonlinearity. Therefore, even "linearly" propagating acoustic waves (e.g., shear waves in an isotropic solid) efficiently generate higher harmonics during reflection and transmission at the interface.[7]

The disrupted bond between faces is characterized by localized extremely high acoustic nonlinearity that originates in the asymmetrical stress profile of an acoustic wave. An intense acoustic wave can even completely break the bonds providing a local dynamic material discontinuity and causing "clapping" or "kissing" effects in the defect area. Such acoustic nonlinear phenomena related to contact acoustic nonlinearity (CAN) are particularly strong in the case of closed microcracks, and these phenomena are a basis for new effective methods for closed microcrack detection and characterization.[18]

NONLINEAR CHARACTERIZATION OF SOLID MATERIALS

Most nonlinear acoustic measurements use a setup where the receiver's frequency is different from that of the transmitter. The nonlinear information is acquired by analyzing either specific spectral components or the overall spectrum of the output signal. As nonlinearity is a second-order phenomenon, amplitudes of both the harmonic and subharmonic components are proportional to the square of the input amplitude. For input voltage 30–100 V, those components are relatively small and often masked by the fundamental frequency. Practically, only a few of the lowest harmonics are observable, and in most cases, only the second harmonic can be detected. Thus, classical nonlinear NDT is primarily "second harmonic NDT." An additional experimental problem is the nonlinearity of the transmitting transducer, which generates waves of harmonics during the excitation of the fundamental acoustic wave. The nonlinear acoustic properties of the media should be derived from the initial distortion of the wave, which can also be caused by frequency-dependent attenuation, diffraction, etc.[19,20] Despite their relatively high excitation voltage requirement, quartz or lithium niobate transducers are often used for the study of nonlinear acoustics because of their rather linear response, which is superior to that of piezoceramic transducers.[21]

Toneburst (RF pulse) mode has been commonly used for nonlinear acoustic investigations. It operates as a compromise between continuous wave and pulse modes, by combining high output power with a signal having a narrow frequency band and reasonable time resolution.

The evaluation of nonlinear effects with longitudinal waves using contact piezoelectric transducers is straightforward (Fig. 1). A tone burst signal from a function generator is fed into a high-power gated amplifier which drives the transmission of the narrow-band lead zirconate titanate transducer. It excites an acoustic wave that propagates along the sample. The acoustic wave with the accumulated harmonic component is received by a second transducer, which can be narrow-band, tuned for a specific harmonic frequency, or wideband to catch entire spectra. Both transmitting and receiving transducers must be aligned along the centerline axis. The measured current and voltage of input signals can be used to calculate a transfer function that converts the received signal to the particle displacement of the incident wave at the receiver. The pulse-inversion technique employs extraction of the second harmonic amplitude by canceling out any odd harmonics. The even harmonic signal is extracted by adding two 180° out-of-phase input signals. Both voltage and current signals of the transmitted ultrasonic waves are recorded and time-averaged with an oscilloscope, and then, transferred to a computer for further signal processing.

The amplitudes of the highest-order harmonics indicate the nonlinear properties of the material. Corresponding nonlinear coefficients can be computed with respect to the amplitude of the fundamental wave.[5] These nonlinear coefficients can be used to characterize the properties of the material. Abnormally high coefficients for a continuous medium indicate internal fracturization of the material with weakened links between grains. Such analysis of only the second harmonic gives the average nonlinear coefficient in the bulk volume of material between the transmitter and the receiver. Thus, assessing the coefficient's spatial distribution is challenging, which is crucial in monitoring and localizing fatigue damage.[22]

Nonlinear wave mixing techniques[23,24] can detect localized damage in a specimen. These techniques are based on compounding two propagating waves in certain resonant or phase-matching conditions (Fig. 2). A third propagating wave called the resonant wave appears as a result of this interaction. The frequency of the resonant wave is different from those of primary waves and their harmonics, which clearly distinguishes the output of nonlinear phenomena in the material from side effects. The amplitude of the resonant wave is proportional to the size of the mixing zone and the acoustic nonlinearity of the material in the mixing zone. Accordingly, the acoustic nonlinearity parameter of the material in the mixing zone can be evaluated by measuring the amplitude of the resonant wave.

Changing the time shift between tone bursts of primary waves provides control over the location of the meeting point of the waves, i.e., the position of the mixing zone. The duration of the primary signals determines the size of the mixing zone, i.e., spatial resolution. This spatial selectivity provides a tool to evaluate the spatial distribution of nonlinear parameters.

The amplitudes of two participating waves decline with distance due to beam divergence and viscosity-caused loss. Consequently, the amplitude of the output signal is a function of mixed zone location, while the acoustic nonlinearity parameter is constant throughout the sample. This function can be approximated by referencing experimental data. Any curve deflection from this baseline function indicates a non-uniform spatial distribution of the nonlinear parameter. Tang *et al.*[25] published the result of measurements for aluminum alloy Al-6061 circular bars with a localized plastic deformation. Figure 3 schematically shows an output of this approach—the amplitude of the output resonant

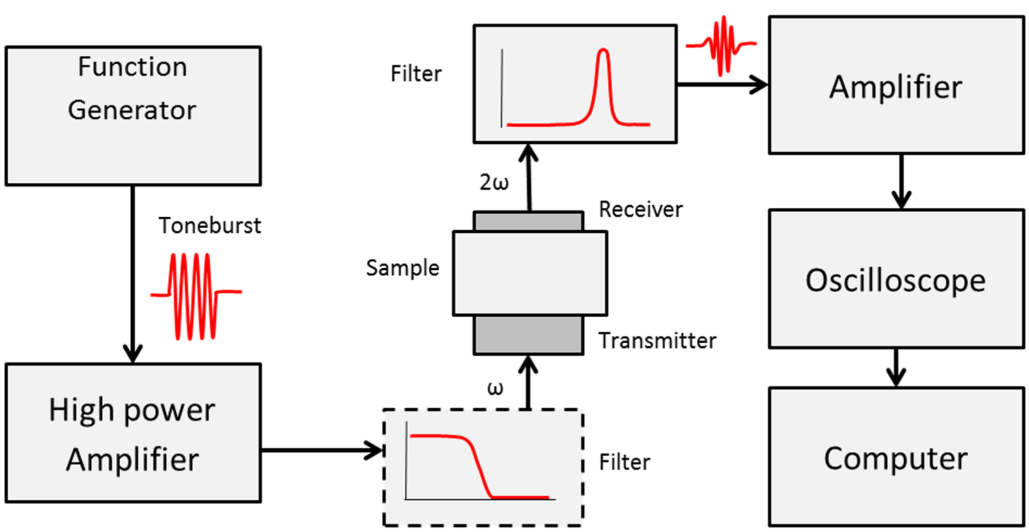

FIG. 1. Schematic of the experimental setup for transmission nonlinear measurements.

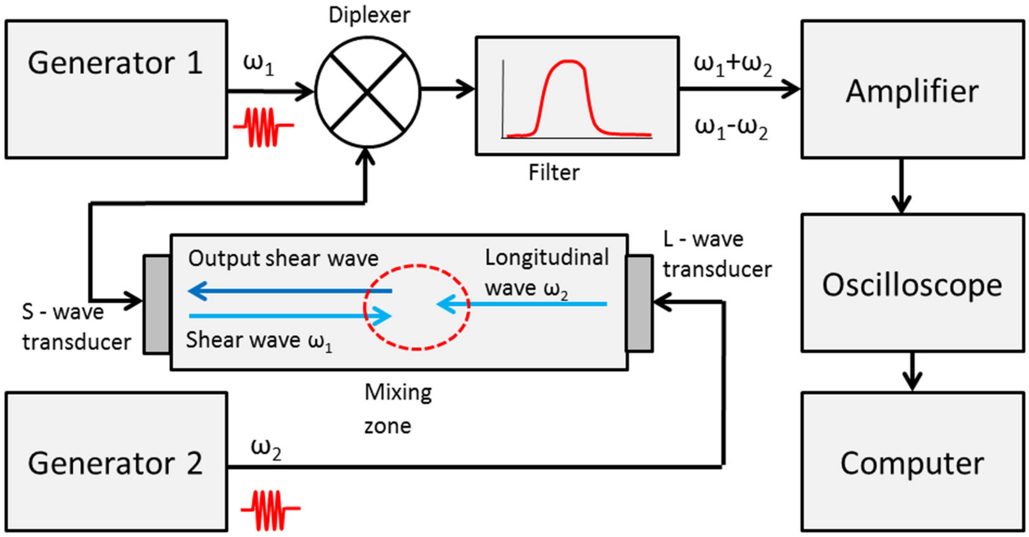

FIG. 2. Schematic of the experimental setup for the collinear wave mixing method.

shear wave as a function of the position of the mixing zone. The gray curve is a baseline function obtained with virgin samples, red—after deformation. Experiments demonstrate the increase of nonlinear parameters inside the plastic area, where the metal's structure is distorted by deformation. The second-order nonlinear coefficients here are three times higher than those of the virgin material, a result of "granulization" of the media due to the development of stress-induced microcracks in the deformed volume. These results provide a methodological foundation for the reverse NDE task: to localize the damaged region and estimate its extent.

Recently, Shan *et al.*[26] proposed a new nonlinear ultrasonic method for nondestructive material characterization. The method is based on a group of newly discovered wave triplets with two primary codirectional shear-horizontal waves mixed in a weakly

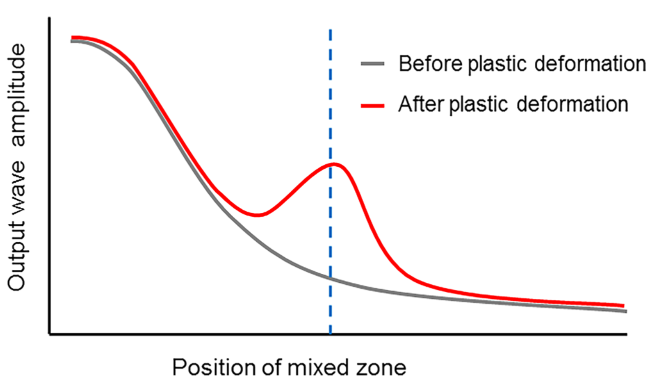

FIG. 3. Typical dependence of amplitude of the resonant shear wave on the position of the mixing zone for the collinear wave mixing setup.

nonlinear plate generating a cumulative Lamb wave at the sum frequency. The authors have demonstrated high sensitivity of the technique for early fatigue damages.

NONLINEAR ULTRASONIC EVALUATION OF ADHESIVE JOINTS

Degraded strength and subsequent failure of adhesive bond joints can result from accumulated fatigue or aging degradation.[27] A weakened bond on the interface often cannot be detected in the early stages using conventional linear ultrasonic NDE methods.[28,29] Some researchers demonstrated that the acoustic nonlinearity parameters are well-correlated with material deterioration. It was shown that even undisturbed bonds have a specific interface-related type of nonlinearity[17,30] that originated in the interaction of the reflected and transmitted waves. Existence of fractured or weakened regions or cracks at the interface results in the intensification of nonlinear phenomena.[31] Nonlinear methods used to assess the quality of adhesive bond joints are based on the local generation of high amplitude vibrations and detection of higher harmonics at the area of excitation. It was clearly demonstrated[32] that the effect of nonlinear resonance in the form of subharmonics generation is effective for discriminating regions of poor adhesion in bonded structures. It is feasible to measure the second and higher harmonics amplitudes directly; however, it requires careful separation of sources. This task becomes easier with the application of the wave mixing method. Two or more primary waves interacting in the bond area generate another different wave. Proper selection of frequencies, polarizations, and directions of propagation for the primary waves allows for the optimization of nonlinear conditions and parameters of the output wave. The generation of the mixed wave is especially efficient if the frequencies of two primary waves meet the resonant condition in the adhesive.[33] Figure 4 illustrates

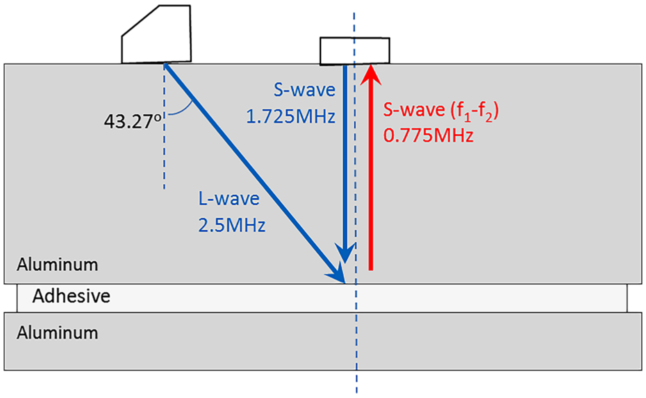

FIG. 4. Experimental setup for wave mixing ultrasonic measurements in an adhesive layer. Reproduced with permission from Ju *et al.*, NDT E Int. **103**, 62–67 (2019). Copyright 2019 Elsevier.

the realized non-collinear interaction of longitudinal 2.5 MHz waves and normally propagated shear 1.725 MHz waves, incident at a certain angle. The interaction results in a normally reflected shear wave with a differential frequency of 0.775 MHz. After phase reversal processing, the nonlinear phenomenon in other parts of the experimental setup can be excluded. The resulting output signal clearly represents the nonlinear properties of the adhesive layer only. The nonlinearity was used to assess the adhesive aging of a different nature. This study demonstrated that the nonlinear coefficient of reflection remains constant throughout the aging time; however, it increases by 82% with thermal aging (Fig. 5).[33]

A sufficient level of initial acoustic waves is required to activate nonlinear phenomena. It can be reached by using high-power electronics or concentrating acoustic energy in a small volume of material. The latter can be achieved by focusing an ultrasonic beam with an acoustic lens. The spatial distribution of nonlinear parameters can be recorded by moving the focal spot across the sample, creating a so-called nonlinear acoustic image. This method was demonstrated in Ref. 34 using Scanning Acoustic Microscopy (SAM) tools.

Another promising method employs a chaotic cavity transducer with the time-reversal technique in order to create high amplitude wave displacement with low input voltage[35,36] (Fig. 6). The experimental setup includes a concave sphere in a highly reverberant medium (aluminum), machined on one corner of a 5 cm cube, which conveys to this object chaotic properties. Two 500 kHz transducers were glued to the side face of the cube. The impulse responses between each transducer and a given point at the surface were recorded during setup calibration. Then, these impulse responses were time-reversed and re-emitted by the transducers leading to a high energy focus at that given point. This procedure results in recompression of the long input signals into short high amplitude pulses of acoustic waves at the focal point at the surface.[36] The wideband receiving channel includes a laser interferometer (Polytec) that is used to measure the normal displacement on the surface.

A test specimen consisted of two aluminum plates glued with epoxy adhesive. An artificial adhesion defect was created by spraying polytetrafluoroethylene on the aluminum substrate prior to bonding. After the system was calibrated, the specimen was placed on the cube using a coupling gel. Attaching the sample to the setup may alter the time-reversal process. Nevertheless, the energy focusing effect is still observed due to a substantial impedance mismatch between the aluminum plate and the coupling gel. The intensity in the focus was sufficient to reveal CAN defects in a bonded joint. The chaotic cavity transducer does not emit the nonlinear component that provides control over the frequency content of the fundamental acoustic wave. The pulse-inversion technique requires two measurements, one with the emission of the appropriate signal and

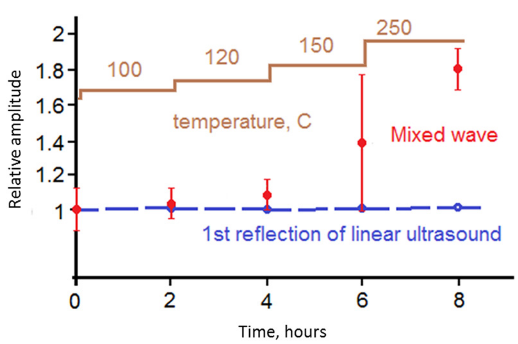

FIG. 5. Increase of mixed wave amplitude with the rise of aging temperature of acrylic adhesive tape. Data used from Ref. 33. Reproduced with permission from Ju *et al.*, NDT E Int. **103**, 62–67 (2019). Copyright 2019 Elsevier.

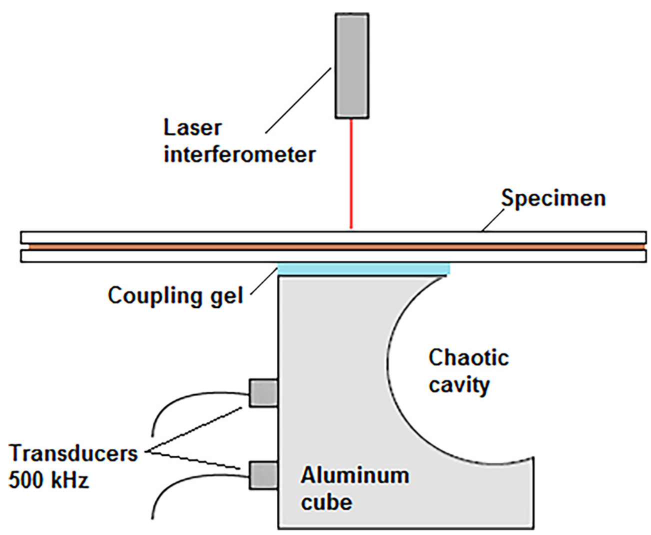

FIG. 6. Nonlinear ultrasonic inspection of adhesion sample using a chaotic cavity transducer. Reproduced with permission from Zabbal *et al.*, J. Phys.: Conf. Ser. **1184**, 012003 (2019). Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY 3.0) license.

the second with the emission of its opposite. Output is the sum of interferometer signals from both measurements, which allows a reduction of the amplitude of the linear response of the system. The spectral composition of the output signal can be revealed by the Fourier transform. Only the fundamental frequency (500 kHz) is present in the signal measured at the reference point (i.e., a good bond). The output signal obtained from the defect area displays the presence of second harmonics.[36] Plotted as a function of position, the second harmonic amplitude will create an image of the defect.

NONLINEAR ACOUSTIC SPECTROSCOPY OF CRACKED FLAWS AND UNBONDS

Classic nonlinear acoustics of solids is based on the anharmonicity of molecular interaction forces. The absence of elastic coupling between faces of a vibrating crack or disbond ("clapping") results in specific local abnormally high contact acoustic nonlinearity. The deformation perpendicular to the crack is characterized by asymmetrical dynamics of contact stiffness. In the compression phase, the stress is higher than in the tensile one because the crack opening is supported by only edge stresses. It can be described as a "mechanical diode" that gives an unconventional nonlinear waveform distortion: a half-period rectification. Such output is characterized by effectively generating both odd and even higher harmonics [Fig. 7(a)]. In the case of transverse deformations, a sliding mechanism plays its role. The faces of the contact interface are mechanically coupled by a friction force. While the contact tangential stiffness changes twice symmetrically over the input strain period, it generates odd higher harmonics only [Fig. 7(b)]. In both cases, the characteristics of contact acoustic nonlinearity and their spectral features are different from those of the classical Hooke's type nonlinearity. Specific characteristics and high localization of contact nonlinear sources make this phenomenon very helpful in developing a new ultrasonic NDE method for crack assessment. Nowadays, approaches proposed in nonlinear NDE include low-frequency (hundreds of Hz) vibration, intermediate-frequency (hundreds of kHz) standing wave, and high-frequency (tens of MHz) propagation modes.[7,8,29]

Low-frequency nonlinear contact vibrations are characterized by the generation of multiple sub- and super-harmonics and corresponding non-monotonous spectra. The model setup, consisting of two metal plates optically polished and pressed together with ambient pressure, allows the demonstration of specific CAN characteristics of the plates' interface at ∼300 Hz.[4] This idealized model demonstrates that the interface "clapping" correlates with the distortion threshold of the contact vibrations accompanied by the generation of multiple higher harmonics. One of the characteristic features of CAN is the oscillating spectra with higher harmonic amplitude modulation similar to a sin(z)/z function. This effect can relate to "pulse" modulation of the interface elasticity, i.e., the stiffness of the interface changes discontinuously during the "clapping" process caused by the driving ultrasound. This behavior is distinctively different from "classical" nonlinearity, when the amplitude of each subsequent harmonic is a few orders less in comparison to the previous.

A model calibration experiment[18] confirms such a generation of high harmonics. The experimental setup represented a disbonded surface consisting of two Al-plates tightened with a bolt. The vibrations were excited in the 500 Hz–1 kHz frequency range with peak acceleration up to 10 g. An accelerometer, with a flat frequency response up to 10 kHz, was attached to the surface of one of the plates to acquire the output signal. Figure 8 shows the nonlinear spectra observed at various contact pressures achieved by tightening the bolt. As the tightening decreased, the spectra started to show characteristic features of the "clapping" CAN mechanism: generation of higher harmonics with non-monotonically oscillating amplitude modulation similar to sin(z)/z. For a fully clamped contact, the residual level of the higher harmonics can be explained by background "clapping" radiation distant from the bolt areas. This background radiation effect should be less significant for materials with high acoustic damping like plastics and composites.

The downside of the method is the inability to provide spatial resolution: it can detect only the presence of the crack but not its location. The modified approach, the nonlinear modulation technique, with the introduction of a high-frequency probe wave in the pulse-echo setting, allows defect localization (Fig. 9). The

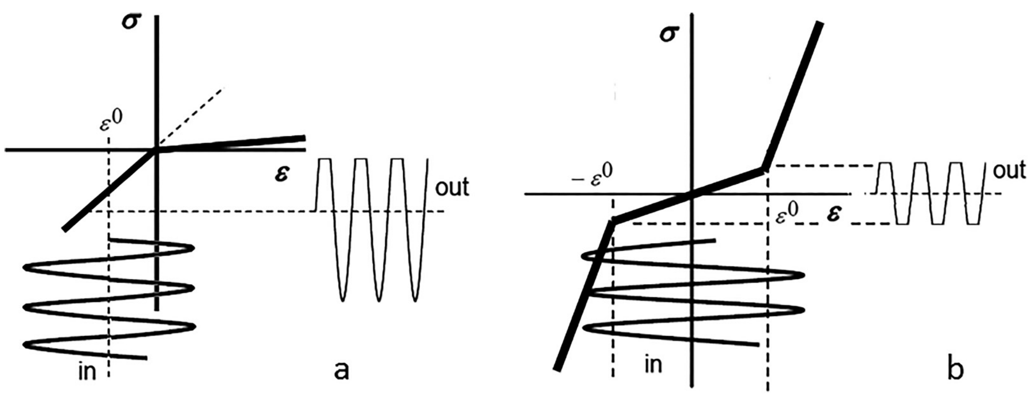

FIG. 7. "Mechanical diode" model for normal (a) and tangential (b) deformations.

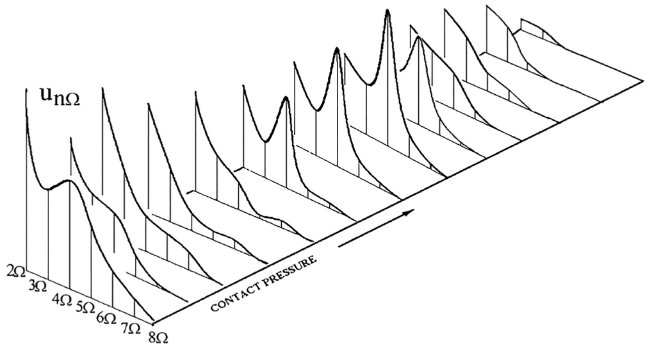

FIG. 8. Low-frequency nonlinear spectra of two Al-plates tightened with a bolt as functions of tightening stress. Reproduced with permission from Maev *et al.*, AIP Conf. Proc. **509**, 1409–1416 (2000). Copyright 2000 AIP Publishing LLC.

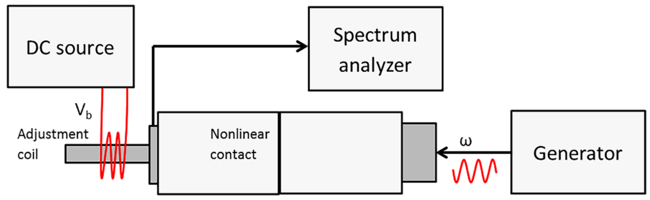

FIG. 10. Resonance measurements of contact nonlinearity.[18]

interaction of intensive low-frequency vibrations with the probe acoustic wave in the crack results in amplitude modulation of the probe wave and the appearance of combined spectral components.[37] This modification allows the distinction between echo signals produced by highly compliant cracks and signals from other scatters.[38] This technique's sensitivity can be sufficient to detect cracks smaller than the wavelength of interacting waves.[39]

Parametric instability that exists in a resonator with a nonlinear contact results in the splitting up of the output spectrum into consecutive subharmonics when the amplitude of the wave increases. Maev and Solodov[18] investigated CAN spectra in the intermediate-frequency range when an acoustic resonator length corresponds to tens or hundreds of wavelengths (Fig. 10). A standing-wave pattern at one of the higher natural resonance frequencies of the sample with a nonlinear contact was generated by a continuous signal with amplitude up to 20 V in the 200–800 kHz frequency range. The contact pressure and corresponding nonlinearity were adjusted by a DC-bias voltage V_b applied to an adjustment coil. A wideband transducer with a resonant frequency higher than the observed spectra (20 MHz) was used to register sample oscillations.

An efficient higher harmonic generation was observed at moderate contact pressure ($V_b \sim 5$ V) [Fig. 11(a)] and it was accompanied by the depletion of the fundamental mode. For weakly pressed contacts ($V_b \sim 1$ V), the vibrations turn unstable. A threshold cascade of multiple subharmonic generations was observed as the input voltage increased [Fig. 11(b)]. The reversal of the typical transformation of the nonlinear spectrum and frequency scaling-down seems to be associated with the dispersion effect, which blocks the higher harmonic generation. In the acoustic resonator with nonlinear contact, a similar effect can be achieved by the phase shifts that go along with the wave reflection. Phase shifts at the "clapping" contact are sensitive to frequency as time-dependent boundary conditions are driven by the fundamental frequency. The nonlinear phenomena in the case of "clapping" contact are observable at moderate amplitudes of the fundamental wave, whereas other nonlinear mechanisms require much stronger input waves in order to be noticeable.

The effect of CAN on HF-acoustic wave (MHz-range) propagation was studied using an experimental setup similar to the one shown in Fig. 10. The nonlinear contact was created between the optically polished surfaces of the sample and the buffer, both made of the same fused silica. An intense 1.5 MHz longitudinal wave pulse was propagated through the sample. The spectrum of the acoustic wave transmitted through the contact was recorded with a 20 MHz output transducer having a wideband frequency response up to 15 MHz. A significant nonlinear distortion of the "rectification" type was observed at a moderate contact pressure [Fig. 12(a)]. Figure 12(b) demonstrates the results of the Fourier transform of the detected waveforms as functions of contact pressure. It is

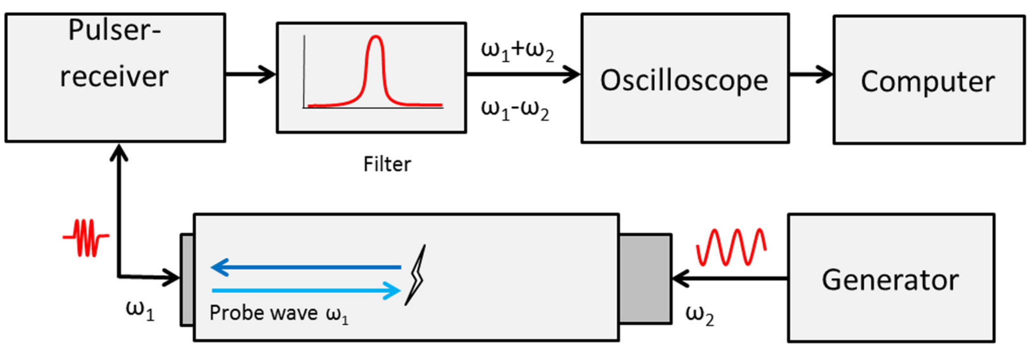

FIG. 9. Crack detection with nonlinear modulation technique.

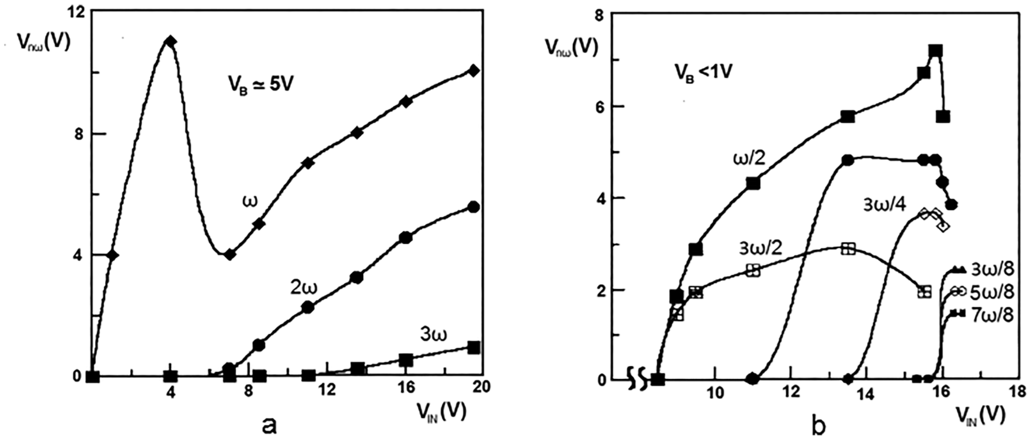

FIG. 11. Higher harmonic (a) and subharmonic (b) amplitudes as functions of the input voltage in acoustic resonators with nonlinear contacts. Reproduced with permission from Maev *et al.*, AIP Conf. Proc. **509** (Part B), 1409–1416 (2000). Copyright 2000 AIP Publishing LLC.

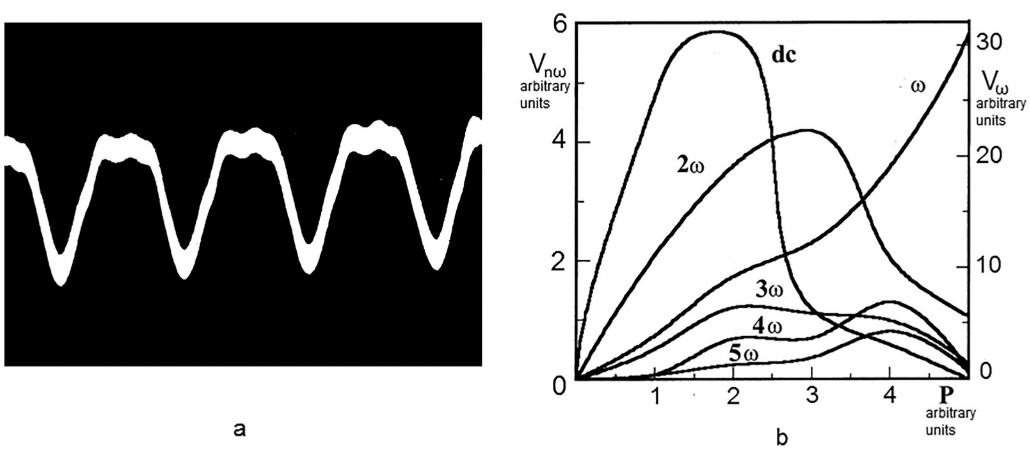

FIG. 12. Nonlinear wave distortion due to CAN (a) and its spectrum components as a function of contact pressure (b). Reproduced with permission from Maev *et al.*, AIP Conf. Proc. **509**, 1409–1416 (2000). Copyright 2000 AIP Publishing LLC.

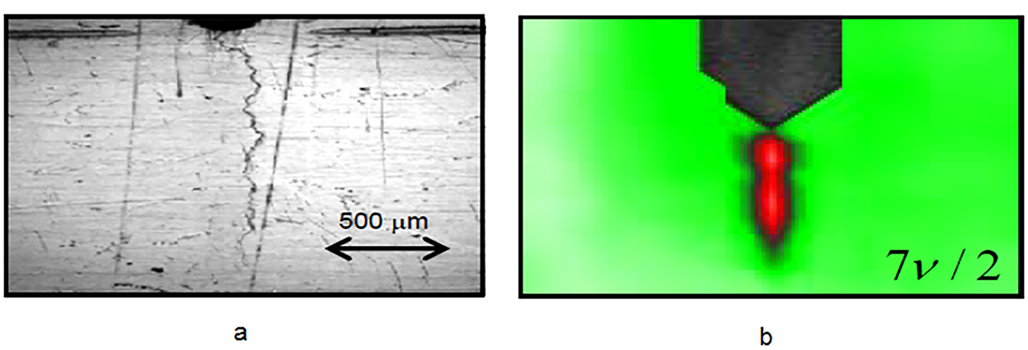

FIG. 13. The microcrack (a) and ultrasonic image obtained in high order subharmonic (b). Reproduced with permission from Solodov, *5th International Workshop of NDT Experts, 12–14 October* (2009). Copyright 2009 Author(s), licensed under a Creative Commons Attribution (CC BY 3.0) license.

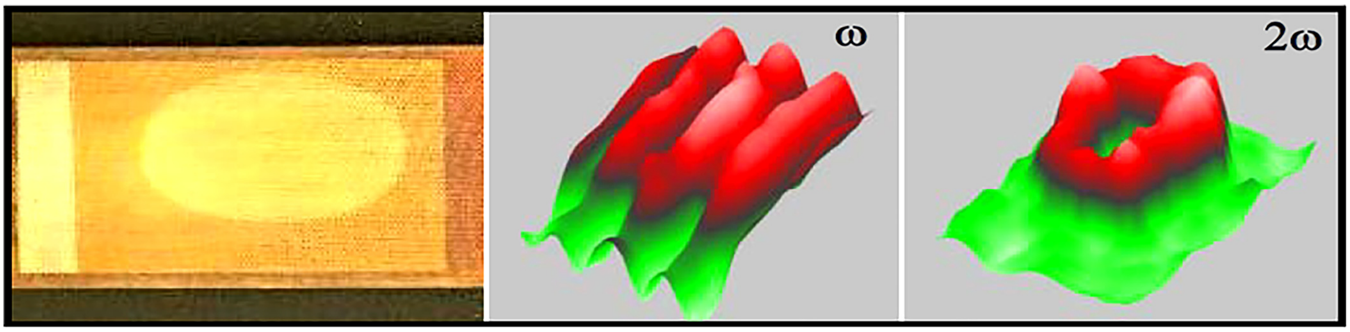

FIG. 14. Fundamental frequency and second harmonic imaging of delamination in a composite. Reproduced with permission from Solodov, *5th International Workshop of NDT Experts, 12–14 October* (2009). Copyright 2009 Author(s), licensed under a Creative Commons Attribution (CC BY 3.0) license.

seen that the CAN spectra depend on pressure at a given wave amplitude. This effect is similar to the non-monotonic spectra in the LF-case. Maximum nonlinearity is observed in conditions of "clapping" contact at the middle of the pressure range. The amplitude of the fundamental wave passed through the contact gradually increases with pressure, demonstrating a smooth transition from open to fully closed contact. It was also noted that a strong constant stress (0-harmonic) accompanied the "rectification" of the acoustic wave. Some increase in amplitudes of the fourth and fifth harmonics was also observed when the boundary was almost closed.

Ultrasonic imaging equipment tuned for receiving harmonics can produce nonlinear acoustic images.[34] The principles actively developed in medical ultrasonic imaging[40–42] can be applied in NDE as well. As an example, Fig. 13(a) depicts a fatigue crack produced by cyclic loading in Ni-based super-alloy.[43] The crack is approximately 1.5 mm long, with a distance between the edges of only 5 μm. The crack is visible on the harmonic image [Fig. 13(b)]. At the same time, conventional linear NDE that utilizes ultrasonic reflection fails to detect cracks of that dimension.

INSPECTION OF COMPOSITE STRUCTURES

The intrinsic inhomogeneity of composite structures and their multi-step manufacturing process often result in various in-born flaws and defects such as matrix cracking, fibre-matrix debonding, delamination, etc. The main type of defect observed in composites is planar delamination—a crack-like separation between layers.[44]

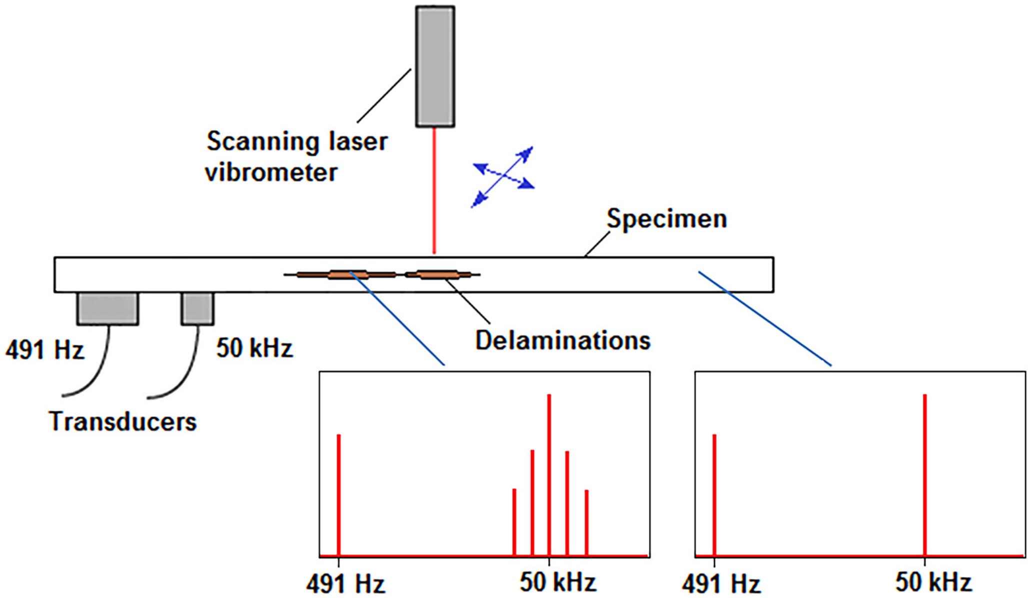

FIG. 15. Power spectra measured at locations with and without delamination on the composite plate.

The contact acoustic nonlinearity which characterizes this type of defect is caused by the mechanical strain between the defect fragments. It becomes an active source of new frequency components, and the high localization of nonlinearity around the origin becomes a basis for nonlinear imaging of composite defects. The intact section of the composite structure shows no frequency variation in the output spectrum, while the damaged region demonstrates a clear nonlinear appearance.

Nonlinear imaging using the second harmonic[9,25,43] was demonstrated for the case of composite delamination. Figure 14 shows oval delamination on top of a piezo-actuator embedded into a glass fiber reinforced composite.[43] Vibrations were excited in the frequency range 20–40 kHz, and their profiles were recorded with a sensitive scanning laser interferometer. After performing a 2D-scan and FFT of the received signals, C-scan images of the defect region for the fundamental frequency and second harmonic were formed. The harmonic images reveal the delamination's boundary ring where clapping and rubbing of the contact surfaces occur. The acoustic image obtained at the fundamental frequency (50 kHz) displays a standing-wave pattern over the area of the actuator only.

The nonlinear vibroacoustic wave modulation technique can also be employed to visualize delamination in composites. The nonlinear modulation sidebands disclose the same localization characteristics as harmonics and can be utilized to visualize damage without increasing bandwidth. For that purpose, surface-bonded piezoceramic transducers were used to excite low (491 Hz) and high frequency (50 kHz) vibrations in carbon/epoxy composite plates.[45] The response was acquired with a scanning laser vibrometer for locations at the predefined grid on the specimen's surface. Power spectra from measured responses were calculated and modulation sidebands around high frequency were selected. The mean value of the amplitudes of the first sidebands was mapped. The level of modulation sidebands was significantly higher around damaged regions compared with the intact fields (Fig. 15). Mapping of the amplitudes of the sidebands produced a resulting image of impact damage in the composite.

CONCLUSION/SUMMARY

Nonlinear acoustic techniques have been extensively developed for quality control of various materials since the 1970s. Researchers have developed the theoretical foundation of nonlinearity principles to describe the effects of dissipation, dispersion, and diffraction during the propagation of intense acoustic waves in multiple media. Experimental research has been conducted to study nonlinear acoustic effects in various solid materials and structures. This intensive study built the groundwork for the practical application of the nonlinear approach for the detection of multiple types of defects and flaws, from an asymmetry of lattice structure and dislocation in crystals to disbonds and cracks in engineering materials. Nowadays, nonlinear acoustic methods have been demonstrated to be useful for biomedical imaging, acoustic microscopy, and nonlinear NDE.

The nonlinear acoustic behavior of materials is affected by the relation between nonlinearity, attenuation, dispersion, and diffraction. Acoustic methods related to the measurement of higher-order elastic constants have been demonstrated to be useful for the material characterization. Nonlinear techniques are effective for the NDE of various flaws in solid materials, such as dislocations in crystals, fractions of precipitates in metallic alloys, microcracks, disbonds, and other defects. The nonlinear elastic properties of solids with micro- and macro-defects can be revealed and used as a measure of "defectiveness" of the material or structural integrity. The instrumental tools besides classical piezoelectric detectors include a wide variety of other detection methods (capacitive, optical, electrodynamic, and accelerometric). A strong correlation between the nonlinear coefficients of materials and the dynamic change of defects in the materials, i.e., material deterioration, was demonstrated in many examples. Therefore, nonlinear measurements can provide unique information regarding material strength and can be used to foresee its failure far in advance. This is especially related to acoustic nonlinear phenomena on contact interfaces that separate intact material and flaws (cracks, grains, disbonds, etc.). Damage detection methods based on nonlinear acoustics have been successfully used to find different types of structural disruptions in materials. However, most of these applications relate to the laboratory rather than real engineering applications. Despite the wide interest and certain advantages, the implementation of ultrasonic nonlinear techniques in industrial practice remains a future task. Nevertheless, the potential of nonlinear acoustics for NDE is significant. Substantial progress has been achieved in that area during the last decade, bringing nonlinear acoustic methods for NDE closer to real industrial and civil engineering applications in the near future.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Roman Gr. Maev: Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **Fedar Seviaryn:** Writing – original draft (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

REFERENCES

[1] S. U. Fassbender, M. Kroening, and W. Arnold, "Measurement of adhesion strength of bonds using nonlinear acoustics," Mater. Sci. Forum **210**, 783–790 (1996).

[2] I.Yu. Solodov, "Ultrasonics of nonlinear contacts: Propagation, reflection and NDE-applications," Ultrasonics **36**, 383–390 (1998).

[3] A. M. Sutin and V. E. Nazarov, Radiophys. Quantum Electron. **38**, 109 (1995).

[4] A. M. Sutin, C. Delclos, and M. Lenclud, "Investigations of the second harmonic generation due to cracks in large carbon electrodes," in *Proceedings of the 2nd International Symposium on Acoustic and Vibration Surveillance Methods and Diagnostic Techniques*, Senlis, France (1995), pp. 725–735.

[5] J. K. Na, W. T. Yost, and J. H. Cantrell, in *Review of Progress in Quantitative Nondestructive Evaluation*, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1993), Vol. 12B, pp. 2075–2093.

[6]V. Lyu, X. Wu, and W. Xu, "Nonlinear acoustic modeling and measurements during the fatigue process in metals," Materials **12**(4), 607 (2019).
[7]Y. Zheng, R. Gr. Maev, and I. Yu. Solodov, "Nonlinear acoustic applications for material characterization: A review," Can. J. Phys. **77**(12), 927–967 (1999).
[8]C. Payan, "Quantitative linear and nonlinear resonance inspection techniques and analysis for material characterization: Application to concrete thermal damage," J. Acoust. Soc. Am. **136**, 537 (2014).
[9]K. Van Den Abeele, "Quantification of material nonlinearity in relation to microdamage density using nonlinear reverberation spectroscopy: Experimental and theoretical study," J. Acoust. Soc. Am. **126**, 963 (2009).
[10]V. Y. Zaitsev, "Nonlinear acoustics in studies of structural features of materials," MRS Bull. **44**, 350–360 (2019).
[11]V. V. Aleshin, S. Delrue, O. Bou Matar, and K. Van Den Abeele, "Nonlinear and hysteretic constitutive models for wave propagation in solid media with cracks and contacts," in *Nonlinear Ultrasonic and Vibro-Acoustical Techniques for Nondestructive Evaluation*, edited by T. Kundu (Springer, Cham, 2019), pp. 175–224.
[12]*Advances in Acoustic Microscopy and High Resolution Ultrasonic Imaging: From Principles to New Applications*, edited by R. G. Maev (Wiley & Sons–VCH, 2013), Monograph, 400 pp.
[13]X. Gong, D. Zhang, J. Liu, H. Wang, Y. Yan, and X. Xu, "Study of acoustic nonlinearity parameter imaging methods in reflection mode for biological tissues," J. Acoust. Soc. Am. **116**(3), 1819–1825 (2004).
[14]J. Sadler, B. O'Neill, and R. G. Maev, "Ultrasonic wave propagation across a thin nonlinear anisotropic layer between two half-spaces," J. Acoust. Soc. Am. **118**(1), 51–59 (2005).
[15]B. O'Neill, J. Sadler, F. Severin, and R. G. Maev, "Theoretical and experimental study of the acoustic nonlinearities at an interface with poor adhesive bonding," Acoust. Imaging **26**, 309–317 (2002).
[16]W. Perez-Regalado, A. Ouellette, A. M. Chertov, V. Leshchynsky, and R. G. Maev, "Joining dissimilar metals: A novel two-step process with ultrasonic monitoring," Mater. Eval. **71**(7), 828–833 (2013).
[17]Y. Shui and I. Y. Solodov, "Nonlinear properties of Rayleigh and Stoneley waves in solids," J. Appl. Phys. **64**, 6155 (1988).
[18]R. G. Maev and I. Y. Solodov, "Nonlinear acoustic spectroscopy of cracked flaws and disbonds: Fundamentals, techniques, and applications," AIP Conf. Proc. **509**(1), 1409–1416 (2000).
[19]B. O'Neill and R. G. Maev, "Integral approximation method for calculating ultrasonic beam propagation in anisotropic materials," Phys. Rev. B **58**, 5479–5485 (1998).
[20]J. Y. Kim, L. Jacobs, and J. Qu, "Nonlinear ultrasonic techniques for material characterization," in *Nonlinear Ultrasonic and Vibro-Acoustical Techniques for Nondestructive Evaluation*, edited by T. Kundu (Springer, Cham, 2019).
[21]G. E. Dace, O. Buck, and R. B. Thompson, *Vibro-acoustic Characterization of Materials and Structures* (ASME, NCA, New York, 1992), Vol. 14, pp. 221–234.
[22]B. E. O'Neill and R. Gr Maev, "Acousto-elastic measurement of the fatigue damage in Waspaloy," J. Res. Nondestr. Eval. **17**(3), 121–135 (2006).
[23]A. J. Croxford, P. D. Wilcox, B. W. Drinkwater, and P. B. Nagy, "The use of non-collinear mixing for nonlinear ultrasonic detection of plasticity and fatigue," J. Acoust. Soc. Am. **126**(5), El117–El122 (2009).
[24]M. H. Liu, G. X. Tang, L. J. Jacobs, and J. M. Qu, "Measuring acoustic nonlinearity parameter using collinear wave mixing," J. Appl. Phys. **112**(2), 024908 (2012).
[25]G. X. Tang, M. H. Liu, L. J. Jacobs, and J. M. Qu, "Detecting localized plastic strain by a scanning collinear wave mixing method," J. Nondestruct. Eval. **33**(2), 196–204 (2014).
[26]S. Shan, M. Hasanian, H. Cho, C. Lissenden, and L. Cheng, "New nonlinear ultrasonic method for material characterization: Codirectional shear horizontal guided wave mixing in plate," Ultrasonics **96**, 64–74 (2019).
[27]R. G. Maev, S. Titov, A. Bogachenkov, B. Ghaffari, K. Lazarz, D. Ondrus, and L. Barsanti, "Ultrasonic evaluation of adhesive coverage in bonded joints using a 2D array technique," Mater. Eval. **71**(7), 875–882 (2013).
[28]E. Y. Maeva, I. Severina, S. Bondarenko, G. Chapman, B. O'Neill, F. Severin, and R. G. Maev, "Acoustical methods for investigation of adhesively bonded structures: A review," Can. J. Phys. **82**, 981–1025 (2004).
[29]B. Ghaffari, J. Dekam, K. Haddix, K. Lazarz, S. Titov, and R.Gr. Maev, "Nondestructive evaluation of adhesively-joined aluminum alloy sheets using an ultrasonic array," SAE Technical Paper 2015-01-0702 (2015).
[30]B. O'Neill and R. G. Maev, "Application of a nonlinear boundary condition model to adhesion interphase damage and failure," J. Acoust. Soc. Am. **120**(6), 3509–3517 (2006).
[31]F. Severin and R. G. Maev, "Adaptive filtration of ultrasonic signals in the evaluation of adhesive bonds in automotive bodies, Insight - Non-destructive Testing and Condition Monitoring," J. Br. Inst. Nondestr. Test. **47**(1), 8–11 (2005).
[32]D. Ginzburg, F. Ciampa, G. Scarselli, and M. Meo, "SHM of single lap adhesive joints using subharmonic frequencies," Smart Mater. Struct. **26**(10), 105018 (2017).
[33]T. Ju, J. D. Achenbach, L. J. Jacobs, and J. Qu, "Non-destructive evaluation of thermal aging of adhesive joints by using a nonlinear wave mixing technique," NDT E Int. **103**, 62–67 (2019).
[34]F. Severin, B. O'Neill, and R. G. Maev, "Image of nonlinear structures of heterogeneous media using the second harmonic in scanning acoustical microscope," AIP Conf. Proc. **509**, 881–888 (2000).
[35]C. Draeger, J. C. Aime, and M. Fink, "One-channel time-reversal in chaotic cavities: Experimental results," J. Acoust. Soc. Am. **105**(2), 618–625 (1999).
[36]P. Zabbal, G. Ribay, and J. Jumel, "Non-destructive evaluation of adhesive joints by using nonlinear ultrasonics," J. Phys. Conf. Ser. **1184**, 012003 (2019).
[37]J. G. Sessler and V. Weiss, Crack detection apparatus and method, U.S. patent 3867836 (1975).
[38]D. Donskoy, A. Sutin, and A. Ekimov, "Nonlinear acoustic interaction on contact interfaces and its use for non-destructive testing," NDT E Int. **34**(4), 231–238 (2001).
[39]V. Zaitsev, V. Nazarov, V. Gusev, and B. Castagnede, "Novel nonlinear-modulation acoustic technique for crack detection," NDT E Int. **39**, 184–194 (2006).
[40]F. A. Duck, "Nonlinear acoustics in diagnostic ultrasound," Ultrasound Med. Biol. **28**(1), 1–18 (2002).
[41]J. N. Potter, A. J. Croxford, and P. D. Wilcox, "Nonlinear ultrasonic phased array imaging," Phys. Rev. Lett. **113**(14), 144301 (2014).
[42]P. Lewin, "Nonlinear acoustics in ultrasound metrology and other selected applications," Phys. Proc. **3**(1), 17–23 (2010).
[43]I. Solodov, "Nonlinear acoustic NDT: Approaches, methods and applications: NDT in progress," in *5th International Workshop of NDT Experts, 12–14 October* (2009), see ndt.net.
[44]F. Severin, A. Denisov, and R. G. Maev, "Analysis of laminated composites with portable ultrasonic imaging," Mater. Eval. **71**(7), 823–827 (2013).
[45]L. Pieczonka, L. Zietek, A. Klepka, W. J. Staszewski, F. Aymerich, and T. Uhl, "Damage imaging in composites using nonlinear vibro-acoustic wave modulations," Struct. Control Health Monit. **25**, e2063 (2017).