



Review

Modelling of nonlinear crack–wave interactions for damage detection based on ultrasound—A review

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ABSTRACT

The past decades have been marked by a significant increase in research interest in nonlinearities in micro-cracked and cracked solids. As a result, a number of different nonlinear acoustic methods have been developed for damage detection. A general consensus is that – under favourable conditions – nonlinear effects exhibited by cracks are stronger than crack-induced linear phenomena. However, there is still limited understanding of physical mechanisms related to various nonlinearities. This problem remains essential for implementation of nonlinear acoustics for damage-detection applications. This paper reviews modelling approaches used for nonlinear crack–wave interactions. Various models of classical and nonclassical crack-induced elastic, thermo-elastic and dissipative nonlinearities have been discussed.

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1. Introduction

It is inevitable that all components and structures demonstrate a process of deterioration of their properties and performance with time. Apart from ageing, observed in many polymers, the main reason for this is initiation and evolution of damage under in-service loading and/or environmental conditions. Although in practice it is possible to foresee ageing or continuous deterioration, severe and/or unexpected structural damage could have fatal consequences. Thus, monitoring for

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structural damage is important in many areas of engineering. Structural health monitoring (SHM) is an online monitoring scheme based on integrated sensors, efficient data transmission, computational power and a processing system [1–4]. A variety of SHM methods have been developed for efficient damage detection. Methods based on ultrasonic wave propagation (e.g., ultrasonic testing or guided ultrasonic waves such as Lamb waves) are particularly attractive and have been exploited for many years [2,5,6]. Most of these methods rely on various linear phenomena of ultrasonic wave propagation. Wave reflections or scattering are often used for damage detection. In contrast, very few techniques described in the literature are based on principles of nonlinear ultrasound.

Nonlinear phenomena can be observed when ultrasonic waves have large amplitude or travel long distances [7]. In these cases sinusoidal waves are often modified and components of smaller amplitudes are dispersed. Physically, these phenomena are caused by different speeds of sound waves in regions of compression and rarefaction [7]. It is also well known that in a nonlinear medium the superposition principle is broken, leading to interaction of waves of different frequencies [7].

Nonlinear properties of elastic waves have been investigated for many years in acoustics, seismology and ultrasonic testing. A classical nonlinear acoustic theory, with observations of higher harmonics, has been formulated in the 18th and 19th centuries [8]; for early studies potential readers are referred, for example, to [9,10] although the most important theoretical formulations and experimental investigations can be traced back to the 1930s when higher harmonics of sound were observed [11]. Probably the next milestone in the development of nonlinear acoustics relates to parametric arrays, studied in Russian and the US laboratories in the 1950s [8,12].

The first signs of nonlinearity in nondamaged solids can be connected with properties of interatomic and intermolecular potentials [12] and have the form of second-order terms in stress–strain relations. Material nonlinearities were investigated extensively with ultrasonic waves in the early 1960s [13,14]. Sub-harmonics, higher harmonics and a so-called *slow dynamic effect* in an excited aluminium ring resonator were observed in the late 1970s [12,15]. Second-harmonic generation on an unbounded interface of a crack was observed experimentally and used for micro-crack detection in [16] and then described theoretically in [17] in the same period of time. A hysteresis in micro-inhomogeneous materials (e.g., rocks) was observed even earlier, in the early 1970s [8,18–20]. All the above developments are now considered to be classical nonlinearities. Studies of various non-classical elastic phenomena in solids have gained much progress since the beginning of the 1990s, mainly in Russia and the USA [12]. Several examples of nonlinear effects have been found in experiments and widely discussed in the literature. The most common effects are [21]:

- Higher-harmonic generation; different mechanisms can generate different harmonics, for example:
 - cubic classical nonlinearity generates only odd harmonics [22];
 - a strain rate-dependent hysteresis generates odd harmonics [22];
- Hysteresis loop in a stress–strain relationship, along with endpoint memory [22–25], i.e. different behaviour of stress–strain curve for loading and unloading;
- Slow dynamics [26–28]: the effect of slow changes (from seconds up to minutes) of material parameters that undergo cyclic excitation, and their return to original value once the excitation is stopped;
- Shift of resonance frequency, accompanied by reduction of amplitude, which is dependent on input wave amplitude [29–33];
- Amplitude-dependent and non-classical (i.e. non-frictional and nonhysteretic) dissipation [8,13], attributed to thermal losses at crack tips or asperities in contact [28,34,35];
- Acoustic equivalent of the Luxemburg–Gorky (LG) effect, i.e. cross-modulation of elastic waves [35,36];
- DC response (envelope demodulation) and sub-harmonic generation [37,38];
- Wave modulation, frequency mixing (vibro-acoustic modulation) [22,23,39–45] – when two waves interact in materials, new frequencies (sidebands) emerge, also combined with the Time Reversal method [21,46,47].

Probably one of the first practical applications of nonlinear acoustics relates to diagnosis of gas bubbles in liquids and – in case of solids – to testing structural integrity of heat-protection coatings of space vehicles [12,48]. Application of various nonlinear wave-propagation features for material testing attracted many research efforts in the first half of the 20th century. Generation of higher harmonics in the presence of damage and a well-known β parameter are good examples. Recent years have seen a high research interest in various methods based on non-classical nonlinear effects associated with ultrasonic wave propagation. Various methods have been used, for instance, for damage evaluation in metallic structures (mainly by observation generation of higher harmonics, also with Lamb and Rayleigh waves) [12,49–55], even of complex shape [22], composites [56], bones [57], soft tissues and biological media [58], concrete [12,59], soil and granular materials [8] and glass [60]. Most of these applications relate to fatigue cracks and fractures. However, some application examples can be found on the detection of delamination [61], corrosion, thermal ageing and hardening [37]. There exist also methods that enable not only detection but also the localisation of damage [12]. Although various studies on methods of nonlinear acoustics in crack detection exist, the investigations that compare those methods with classical ultrasonic NDT are not so popular. Ryles in [51] compared the nonlinear acoustics-based method, including the modulation of low- and high-frequency waves, with guided Lamb waves for detection of a fatigue crack in an aluminium plate. Both methods enable the detection of cracks with similar dimensions; however, the results of testing with Lamb waves were more difficult to interpret.

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