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On some aspects of material behavior relating microstructure and ultrasonic higher harmonic generation

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ABSTRACT

This article investigates some important aspects of material behavior responsible for acoustic nonlinearity. Even though the discussion is based on a specific constitutive model used for studying higher harmonic generation, the conclusions drawn are valid in a general context. Three aspects of material behavior, namely tension–compression asymmetry, shear-normal coupling and deformation induced anisotropy are presented. The role of each in the generation of higher harmonics along with the plausible microstructural features that contribute to such behavior is discussed. First and foremost, tension–compression asymmetry is identified to cause second (even) harmonic generation in materials. Then shear-normal coupling is identified to cause generation of secondary waves of different polarity than the primary waves. In addition, deformation induced anisotropy due to the presence of residual stress/strain and its contribution to acoustic nonlinearity is qualitatively discussed. Meso-scale modeling aspects to accurately predict the effect of microstructure on higher harmonic generation are emphasized throughout.

1. Introduction

The need to characterize the current state of a material is fundamental to structural health monitoring (SHM), the prediction of remaining useful life, and condition based maintenance of structural systems. An ability to detect and characterize material degradation in advance of the initiation of macroscale damage would have a tremendous impact on the life cycle costs of many structural systems. State of the art SHM technologies are limited to detection of macroscale damage, but nonlinear ultrasonics (Jhang, 2009; Zheng, Maev, & Solodov, 2000) has strong potential to shift the first detection of material degradation significantly earlier in the life of the structural system. In this context nonlinear ultrasonics refers to the phenomenon where a monochromatic wave propagating in the material is distorted due to the material nonlinearity. The distortion causes higher harmonics to be generated at integer multiples of the primary excitation frequency, and thus the higher harmonics are sensitive to the material nonlinearity. Physically, the material nonlinearity is associated with lattice anharmonicity; i.e., it is due to the presence of non-quadratic interatomic potentials that govern the atoms in the solid (Landau & Lifshitz, 1970). The objective of this paper is to identify aspects of material behavior that are responsible for ultrasonic higher harmonic generation in materials. These aspects are most relevant when describing the meso-scale behavior of material where the effect of microstructure is prevalent. This understanding enables us to correlate higher harmonic generation with microstructure by evaluating the contribution of the latter to the pertinent aspects of material

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behavior to be discussed. This study also sheds light on the features that a (meso-scale) constitutive model should incorporate for it to predict harmonic generation. Below, we present a brief review of some earlier work on the theory and experimental aspects of nonlinear ultrasound for characterizing material state.

The generation of higher harmonics in metals was discovered by Breazeale and Thompson (1963) and investigated further by Hikata, Chick, and Elbaum (1965). An interesting feature of the higher harmonics is that their amplitudes increase over their propagation distance. A simple 1D nonlinear stress–strain relation (Eq. (1)) is often employed;

$$\sigma = E\epsilon(1 + \beta\epsilon) \tag{1}$$

where σ is the stress, 'E' is the Young's modulus, ϵ is the strain and β is a nonlinear parameter that quantifies the nonlinearity. Hikata et al. (1965) concluded that harmonic generation in the presence of bias stresses occurs due to dislocation motion as well as lattice anharmonicity. Hikata and Elbaum (1966a) further studied the dislocation dynamics on generation of second and third harmonics and Hikata and Elbaum (1966b) conducted third harmonic experiments on single crystal aluminum to confirm the theory of Hikata and Elbaum (1966a). Buck (1976) used harmonic generation to measure internal stresses produced by dislocations. Later, Cantrell and Yost (2001) modeled second harmonic generation associated with dislocation dipole substructures during fatigue and provided some experimental results. Their work on fatigue is extended in a series of papers by Cantrell (2004, 2006, 2009). Cash and Cai (2011, 2012)used dislocation dynamics simulations to study the effect of a bias stress on the acoustic nonlinearity parameter. They found that an orientation dependent line energy is necessary to correlate dislocation dynamics with the acoustic nonlinearity parameter. These results contradict the previously mentioned modeling efforts. Thus, while modeling progress has clearly been made there is still a strong need for improved understanding of the correlation between higher harmonic generation and microstructure.

Furthermore, phenomenological evidence exists that higher harmonic generation is sensitive to other modes of material degradation; e.g., thermal aging (Kim & Lissenden, 2009), creep (Baby et al., 2008; Valluri, Balasubramaniam, & Prakash, 2010; Xiang, Deng, & Xuan, 2014) and radiation damage (Matlack et al., 2012). All of these modes of degradation are linked to some type of microstructure evolution, which in turn must somehow be connected to nonlinearity that results in higher harmonic generation. In this vein Johnson and coworkers (Van Den Abeele, Johnson, & Sutin, 2000a) (Van Den Abeele, Johnson, & Sutin, 2000b) have coined the term mesoscopic elastic materials, meaning materials that exhibit nonlinear elastic behavior associated with some microstructural feature, such as distributed microcracks or a long macrocrack. These authors emphasize the large affect that damage has on nonlinear behavior. Our immediate interest is similar, except that we seek to characterize the fairly small effects of minute changes of the material. Additionally, most research has focused on the acoustic nonlinearity parameter β, or the relative nonlinearity parameter, which may not always provide the best description of evolving material state, especially when there are multiple mechanisms in competition. Creep may be a good example, as Xiang et al. (2014) showed the nonlinearity parameter to increase and then decrease with creep strain rather than to monotonically increase.

As ultrasound is used to probe damage in the material, it is necessary to understand the essential features of higher harmonic generation in the material. A simple model can be obtained by using the conservation of linear momentum in conjunction with Eq. (1) and a linearized strain–displacement relation, which gives the 1D nonlinear wave equation

$$\rho\frac{\partial^2 u}{\partial t^2} = E\left(1 + \beta\frac{\partial u}{\partial x}\right)\frac{\partial^2 u}{\partial x^2} \tag{2}$$

which, along with the boundary condition $u(0,t) = u_0\cos(\omega t)$, can be solved using a perturbation approach (Cantrell, 2004) to yield

$$u(x,t) = \frac{1}{8}\beta k^2 u_0^2 x + u_0\cos(kx - \omega t) - \frac{1}{8}\beta k^2 u_0^2 x\cos(2kx - 2\omega t) \tag{3}$$

where ω is the frequency of the wave and k denotes its wavenumber. Clearly, both the static (zero-frequency) component and the second harmonic increase linearly with propagation distance. The modal amplitude ratio, $\frac{A_2}{A_1^2} = \left|\frac{\beta k^2 x}{8}\right|$, also known as the relative nonlinearity parameter and often measured in experiments is an indirect indicator of material evolution. Here, A_1 and A_2 denote the amplitude of primary and second harmonic waves respectively. Thus, it is essential to have a thorough understanding of the plausible degradation mechanisms to evaluate the material state. It should also be pointed out that while 1D equations suffice for bulk wave propagation, 3D equations are more appropriate for guided wave modes.

Ultrasonic waves are sensitive to the collective effects of lattice defects (e.g., dislocation monopoles, dipoles, line lengths, precipitates, persistent slip bands). They do not however exhibit sensitivity to individual lattice defects. Thus, the comprehensive understanding provided by models at the length scale of the ultrasonic wavelength should be valuable for studying higher harmonic generation in polycrystalline metals. To that end, some salient aspects of material behavior that contribute to harmonic generation in materials are discussed and the role of each in ultrasonic higher harmonic generation is presented. In addition, relevant features of microstructure that contribute to such material behavior are outlined. These aspects provide a deeper understanding and also serve as a way to quantify the meso-scale effect of microstructure on harmonic generation. By "microstructure" we refer to any of the following that are responsible for ultrasonic higher harmonic generation: crystal lattice, dislocations, precipitates, voids, micro-cracks, etc. The focus of this article is not to quantify harmonic generation from a particular "microstructure", but to identify aspects of material behavior that are responsible for higher harmonic