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Second harmonic reflection and transmission from primary S0 mode Lamb wave interacting with a localized microscale damage in a plate: A numerical perspective

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ABSTRACT

Second harmonic generation has been widely used in characterizing microstructural changes which are evenly distributed in a whole structure. However, few attention has been paid to evaluating localized micro-scale damages. In this paper, second harmonic reflection and transmission from the primary S0 mode Lamb wave interacting with a localized microstructural damage is numerically discussed. Schematic diagram for deriving fundamental temporal waveform and reconstructing the second harmonic temporal waveform based on Morlet wavelet transform is presented. Second harmonic reflection and transmission from an interface between the zones of linear elastic and nonlinear materials is firstly studied to verify the existence of interfacial nonlinearity. Compositions contributing to second harmonic components in the reflected and transmitted waves are analyzed. Amplitudes of the reflected and transmitted second harmonic components generated at an interface due to the interfacial nonlinearity are quantitatively evaluated. Then, second harmonic reflection and transmission from a localized microscale damage is investigated. The effects of the length and width of a microscale damage on WCPA (wavelet coefficient profile area) of the reflected and transmitted second harmonic components are studied respectively. It is found that the second harmonic component in the reflected waves mainly reflects the interfacial nonlinearity while second harmonic in the transmitted waves reflects the material nonlinearity. These findings provide some basis on using second harmonic generation for characterization and detection of localized microstructural changes.

1. Introduction

The use of nonlinear ultrasonics for characterizing microstructural change, tracking structural degradation, evaluating micro-scale damages and detecting micro cracks has proven to be a promising technique in nondestructive evaluation [1–6]. Of various techniques under a broad discipline of nonlinear ultrasonics, second harmonic generation [7] is most frequently used. Early analytical studies illustrated that material nonlinearity [8], dislocation [9,10], persistent slip bands [11,12], and precipitation characteristics [13] contribute to second harmonic generation. Based on these theoretical investigations, many experimental studies were conducted to evaluate fatigue damage in various materials, i.e., structural steel [14], nickel-base superalloy [15] and Ti-6Al-4V [16]. In addition to fatigue damage, nonlinear ultrasonics was also used to detect other failure mechanisms, i.e., hardening [17], thermal aging [18] and radiation damage [19]. In these above analytical or experimental studies, bulk waves were used.

Compared to the point-to-point inspection style of bulk waves, ultrasonic Lamb wave technique [20–23] is quite efficient and cost-effective as Lamb waves can propagate a very long distance with little loss in energy and they can also be applied to interrogating physically inaccessible areas of structures. Nonlinear Lamb waves have emerged as a promising alternative for evaluating microstructural change preceding the initiation of macro-scale damages as they combine the early micro-scale damages detection capability of nonlinear method with efficient inspection approach of Lamb waves. A review on nonlinear guided waves nondestructive

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evaluation by Chillara and Lissenden [24] was published quite recently. Initial work by Deng [25] and De Lima and Hamilton [26] derived two necessary conditions, namely phase velocity matching and none-zero power flux criterion for cumulative second harmonic generation of Lamb waves in plates. This was later extended by authors [27–29] to study mode interaction and generalized harmonic generation. The work [30] on mode selection that is the key for efficient cumulative second harmonic generation was also addressed. Along with these analytical studies, experimental studies using S1-S2 mode pair were conducted to characterize material nonlinearity [31], elastic anisotropy [32], tensile plasticity-driven damage [33], fatigue damage [34–36], thermal fatigue [37], creep damage [38–40] and surface property [25]. Recently, Wan [41] proposed using approximate phase velocity matching based nonlinear S0 mode Lamb waves for the detection of evenly distributed microscale damages. It should be noted that these above studies relied on the assumption that the microstructural changes are globally and uniformly distributed in the whole structures.

In addition to the research on globally distributed microstructural damages, detection of microcracks has also received considerable interest. Examples of micro cracks evaluation using nonlinear Lamb waves are addressed in [42–45]. However, few attention has been paid to localized microstructural change which means that micro-scale damage is assumed to be uniformly localized at a certain region but not evenly distributed in the whole material. Recently, Lissenden et al. [46] used the amplitude ratio A_3/A_1^3 to quantify the localized plastic strain. Chillara and Lissenden [47] numerically studied the effect of periodical distribution, intensity and spatial extent along the propagation direction of the localized microscale damage on second harmonic generation. In these two studies, transmitted second harmonic amplitude is derived, however, its compositions are not analyzed. Furthermore, second harmonic reflection is not considered.

Initial work on nonlinear reflection was addressed in [48,49]. Later study was extended to second harmonic reflection from a contacting interface of two different media [50], anisotropic solids [51], same aluminum structure [52–54], and a stress-free boundary [55]. In these investigations, bulk waves were used to study second harmonic reflection from a contacting interface.

In this study, second harmonic reflection and transmission characteristics from the primary S0 mode Lamb waves interacting with a localized microscale damage are discussed in more detail. Compared to the traditional phase velocity matching based nonlinear Lamb waves, the merits of using nonlinear S0 mode Lamb waves is briefly stated as follows. First, nonlinear S0 mode Lamb waves at low-frequency range is more robust. Second, exciting a single desired S0 mode Lamb wave is much easier and few unwanted modes would be generated. Third, it is suitable for detecting micro-scale damages or micro cracks buried in the interior of a large-scale structure. The main contributions of this paper are stated as follows. First, the existence of interfacial nonlinearity at an interface between linear elastic and nonlinear materials is verified. Second, compositions of the reflected and transmitted second harmonics are identified and quantitatively evaluated. Third, effects of the length and width of localized microscale damage on amplitudes of the reflected and transmitted second harmonics are studied respectively.

We would like to note that in the context of nonlinear ultrasonics, micro-scale damage is always modelled as some kind of elastic nonlinearity in the stress-strain relationship or equivalently including higher order terms in the strain energy function [47]. In this paper. "LE" denotes the linear elastic material and "NL" denotes the nonlinear elastic material used to represent the presence of microscale damages. The terms "micro-scale damage", "microstructural damage", "microstructural change" and "material degradation" are synonymously used to replace "nonlinearity" in this article as stated in the previous study [47]. The rest of this paper is organized as follows. The methodology is briefly introduced in Section 2. Numerical studies are conducted and results are presented in Section 3. Conclusions are draw at last in Section 4.

2. Methodology

2.1. Reflection and transmission of longitudinal wave from a contacting interface

One dimensional schematic model for studying a contacting interface is illustrated Fig. 1 [52,54]. It is obviously illustrated that by applying pressure p_0, two elastic solids are contacted together to form a contacting interface. As the surfaces of these two solids are not ideal smooth and flat, the interface gap is in existence. In the absence of longitudinal wave propagation, these two solids are at equilibrium under nominal contact pressure p_0 with the equilibrium gap distance h_0. Previous studies [52–54] have shown that when a monochromatic incident longitudinal wave propagates across the contacting interface, reflected and transmitted waves contain fundamental and second harmonic components.

The fundamental amplitude reflection coefficient defined as the ratio of absolute amplitude of the fundamental component in the reflected wave to the amplitude of the incident wave is expressed by [52]

$$R^{(1)} = \frac{A_{Re}^{(1)}}{A_{In}} = \frac{1}{\sqrt{1+\frac{4K_1^2}{\rho^2c^2\omega^2}}}, \tag{1}$$

and the fundamental amplitude transmission coefficient which is characterized as the ratio between the absolute amplitudes of the fundamental component in the transmitted wave and the incident wave is given by [52]

$$T^{(1)} = \frac{A_{Tr}^{(1)}}{A_{In}} = \frac{2K_1}{\rho c\omega\sqrt{1+\frac{4K_1^2}{\rho^2c^2\omega^2}}}, \tag{2}$$

where $R^{(1)}$ and $T^{(1)}$ refer to the fundamental amplitude reflection and transmission coefficients respectively; $A_{Re}^{(1)}$ and $A_{Tr}^{(1)}$ denote the amplitudes of the fundamental components in the reflected and transmitted waves; A_{In} is the amplitude of the incident wave; ρ, c and ω denote the density, wave velocity of the contacting solids and the angular frequency of the incident wave; K_1 refer to the linear interfacial stiffness.

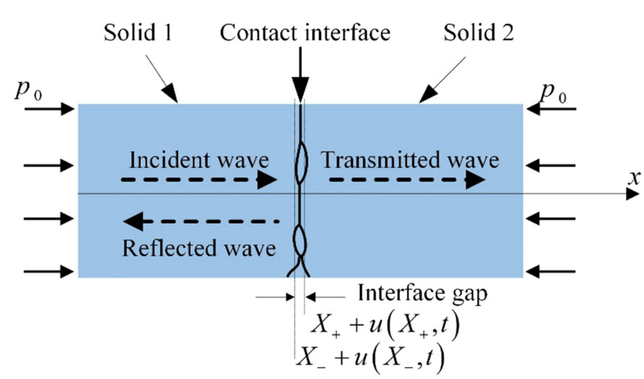

Fig. 1. Schematic model of longitudinal wave propagating through a contact interface between two linear elastic solids [52,54].