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Second harmonic generation at fatigue cracks by low-frequency Lamb waves: Experimental and numerical studies

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A B S T R A C T

This paper presents experimental and theoretical analyses of the second harmonic generation due to non-linear interaction of Lamb waves with a fatigue crack. Three-dimensional (3D) finite element (FE) simulations and experimental studies are carried out to provide physical insight into the mechanism of second harmonic generation. The results demonstrate that the 3D FE simulations can provide a reasonable prediction on the second harmonic generated due to the contact nonlinearity at the fatigue crack. The effect of the wave modes on the second harmonic generation is also investigated in detail. It is found that the magnitude of the second harmonic induced by the interaction of the fundamental symmetric mode (S_0) of Lamb wave with the fatigue crack is much higher than that by the fundamental anti-symmetric mode (A_0) of Lamb wave. In addition, a series of parametric studies using 3D FE simulations are conducted to investigate the effect of the fatigue crack length to incident wave wavelength ratio, and the influence of the excitation frequency on the second harmonic generation. The outcomes show that the magnitude and directivity pattern of the generated second harmonic depend on the fatigue crack length to incident wave wavelength ratio as well as the ratio of S_0 to A_0 incident Lamb wave amplitude. In summary, the findings of this study can further advance the use of second harmonic generation in damage detection.

1. Introduction

1.1. Lamb waves

Over the lifespan, engineering structures accumulate mechanical damage due to fatigue, temperature variations, effects of aggressive environment and aging. Without proper inspection and maintenance strategies to ensure the safety and integrity of the structures, the accumulation of the damage can lead to catastrophic consequences. Therefore, the development and deployment of non-destructive evaluation (NDE) and structural health monitoring (SHM) are critical to ensure the structural safety, minimize the maintenance costs, and extend the service life of the structures.

Among various NDE and SHM techniques, Lamb wave has attracted significant attention due to its outstanding properties, such as ability to propagate a long distance, able to provide rapid inspection, high sensitivity to many types of mechanical

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damages, and detection of damages at inaccessible at locations [1–4]. In the last two decades, different Lamb wave based techniques [5–9] have been developed for damage detection. The majority of the developments focused on linear Lamb wave that determines the presence of damage based on the change of wave speed, reflection and transmission, or mode conversion [10] of the linear wave signals, i.e. the scattered wave at the same frequency as the incident wave [11–13]. The linear features of Lamb wave are sensitive to damages with sizes comparable to the wavelength of the incident wave, e.g. corrosion spot [14,15] or crack [16–18]. However, they are not effective in detecting early stage of mechanical damage, e.g. micro-damage and small fatigue crack. In addition, most of the damage detection techniques based on the linear Lamb wave require baseline data [19] to extract the scattered wave signal from the damage. But the change of environmental conditions, e.g. temperature variation [20–22], stress level [23] could make the baseline subtraction fail in extracting the scattered waves signal from the damages. Therefore, there is a need to overcome the aforementioned deficiencies of the linear wave signals to achieve effective and practical damage detection.

1.2. Nonlinear Lamb waves

Nonlinear ultrasonic techniques detect the incipient damage based on nonlinear phenomena, such as higher harmonic generation [24], sub-harmonic generation [25], mixed frequency response [26,27] and nonlinear resonance [28]. A number of studies have demonstrated that the nonlinear characteristics and phenomena are more sensitive to the presence of contact-type damage, such as fatigue crack and delamination, and have less influence by environmental change than the linear features.

Early developments of the nonlinear ultrasonic techniques focused on the nonlinearity of elastic bulk waves [29–31]. Recently, several studies have focused on the nonlinearity of Lamb waves [32]. Compared to the nonlinear ultrasonic techniques based on the bulk waves, nonlinear Lamb waves could provide long-range inspection for thin-wall structures. A number of studies have demonstrated that the generation of second- or third-order harmonics could be used to determine the presence and severity of incipient damage in structures [33]. The generation of higher harmonics involves various nonlinear phenomena. However, recent studies have primarily focused on the investigations of the higher harmonic generation due to nonlinear elasticity [24,34] and contact nonlinearity [35,36].

The early damage accumulation usually leads to the deviation of the stress-strain behavior from the linear Hook's law. The higher harmonics are generated due to this nonlinearity in the elastic behavior of the material, and this provides a way for the measurement and quantification of the micro-damage. The material nonlinearity normally leads to distortion of propagating waveforms, and hence, it generates the higher harmonic. A number of studies focused on the material nonlinearity were performed by several researchers [24,34–39].

Lamb waves are dispersive and have multi-mode nature, which make accurate experimental realization of nonlinear Lamb wave become difficult. As illustrated in the aforementioned studies, the phase and group velocity matching are essential conditions to generate cumulative behavior of the second harmonic, i.e., the magnitude of second harmonic increases with wave propagation distance [24]. These conditions ensure that the second harmonic Lamb wave can propagate a reasonably long distance and can be detected. Pruell et al. [34] found that the plasticity-induced damage can cause the second harmonic generation. Li et al. [37] employed the second harmonic Lamb waves to assess thermal fatigue damage in composite laminates. Zhou et al. [38] carried out an experiment study to demonstrate that the higher harmonic Lamb wave can be used to evaluate the fatigue crack. They found that the nonlinearity contributed by the material itself, i.e. the nonlinear elasticity effect, is insignificant compared with that induced by the fatigue damage.

When Lamb wave interacts with contact-type of damage, e.g. fatigue crack [35] and delamination [40,41], higher harmonics can be generated due to the contact nonlinearity. This happens due to the nonlinear interaction of the crack surfaces caused by the incident Lamb wave. When the incident wave passes through the crack, the compressive pressure of the incident wave closes the crack and the tensile pressure opens the crack. As a result, the compressive part of the incident wave penetrates the crack, while the tensile part cannot. This phenomenon is schematically illustrated in Fig. 1. This clapping behavior at the crack surfaces causes the nonlinearity, and hence, generating the higher harmonics due to the effect of localized nonlinearity [33].

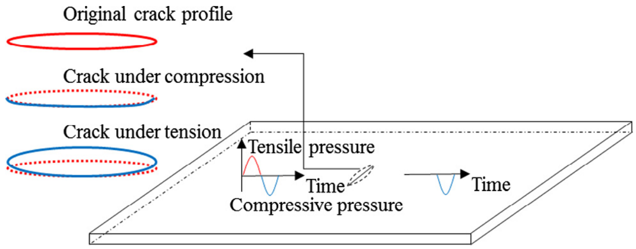

Fig. 1. Concept of contact nonlinearity at a fatigue crack.