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Scanning non-collinear wave mixing for nonlinear ultrasonic detection and localization of plasticity

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ABSTRACT

Non-collinear wave mixing recently has been proposed to detect and localize micro-damage in materials. It is proved sensitive to the interaction angle α of the incident waves. In this work, the relationship between the acoustic nonlinearity parameter χ and the α is studied by numerical simulations and experimental measurements based on the nonlinear interaction of two shear waves. A single-peak change in the normalized acoustic nonlinearity parameter χ' of the mixing wave versus the incident angle is observed from numerical simulations and then is verified by experiments. The results show a -6 dB decrease of χ' corresponds to a deviation of about 4° in the incident angle. Meanwhile, the detection and localization of plastic deformation is also conducted on an aluminum alloy based on the scanning of non-collinear wave mixing, in which the distribution of the acoustic nonlinearity is similar to that of the plastic strain.

1. Introduction

Plastic deformation has been widely applied to change the mechanical strength of the metallic material in order to satisfy the requirements in chemical, nuclear and aerospace industries, while an excessive plastic deformation will likely lower the ductility of metals and lead to an early failure of structures and components [1]. Therefore, the detection and localization of the excessive plastic deformation caused by the loading force is important for the safety control of the structures and components. It was reported that the plastic deformation will cause microstructure evolution, such as the multiplication and motion of dislocations, the deformation-induced phase change, and the deformation of micro-cracks [2,3]. Nondestructive evaluation (NDE) of materials for microstructure evolution or material degradation has attracted considerable attention in the past decades. In recent years, nonlinear ultrasonic techniques have been developed for the characterization of microstructures, deformation mechanisms and the assessment of creep and fatigue damages [4–20].

The nonlinear ultrasonic technique possibly offers a promising means for the nondestructive evaluation of structural integrity owing to its sensitivity to material degradation as compared to the linear ultrasonic parameters [4]. In particular, the generation of higher harmonics has been extensively studied for nonlinear ultrasonic detection of plasticity, creep and fatigue damages [7–20], in which the material nonlinearity caused by damages can be quantified by acoustic nonlinear parameter β based on the ratio of the amplitude of the second harmonic to the fundamental wave. However, the measured β generally is an average value regarding the damages in the region between the transmitter and the receiver, which is also possibly contaminated by external nonlinearity (i.e. the equipment, coupling medium etc.). In order to localize and characterize a local micro-damage, wave mixing method was recently proposed as an alternative [21–28]. Two different approaches usually are adopted in wave mixing: collinear wave mixing [21–24] and non-collinear wave mixing [25–28], when two waves intersect at a certain angle and a third resonant wave will be generated in the intersection region. The second approach non-collinear wave mixing is used here, and will be discussed in more details.

Croxford et al. reported the application of non-collinear wave mixing to the ultrasonic measurement of material nonlinearity to assess plasticity and fatigue damages, whose results demonstrated that the non-collinear wave mixing is sensitive to the changes due to plasticity and fatigue damages [25]. Recently, non-collinear wave mixing technique was also presented to characterize the bond quality of titanium diffusion bonds, in which the experiments showed that near perfected diffusion bonds can be easily separated from the partial bonds to which the linear ultrasonic approaches exhibited no sensitivity [26]. Besides the metallic alloys, the non-collinear wave mixing was also adopted to evaluate the

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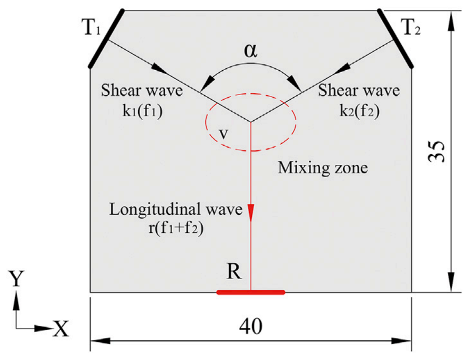

Fig. 1. Geometry of the model used to research the non-collinear wave mixing, where $\mathbf{k}_1$ and $\mathbf{k}_2$ are the wave vectors of two shear waves respectively, $\mathbf{r}$ is the wave vector of the third longitudinal wave, v is the interaction volume in a nonlinear elastic material. The dimensions are in mm.

physical ageing state in polymers, such as Polyvinylchloride (PVC) [27]. The non-collinear wave mixing was proved sensitive to the deviation of the incident angle of mixing wave [29,30]. A numerical analysis of the nonlinear wave beam pattern under imperfect wave-mixing condition was performed to study the incident angle deviation of wave mixing [29]. Meanwhile, the influence of the incident angle has been analyzed in Ref. [30], in which a "mountain-shape" change of the longitudinal wave amplitude versus the incident angle was obtained from numerical simulations. However, there is less information with respect to the studies of the influence of incident angle on the generation of the non-collinear wave mixing. Specifically, a tolerable deviation of an actual incident angle from the ideal resonance angle ($\alpha_r/2$) is also needed for solving problems with unknown material properties or for problems where only an estimate of the material properties is available.

The aim of this work is to study the problem of deviation of the incident angle and give a suitable deviation of incident angle. First, numerical simulations are carried out in the nonlinear material to verify the nonlinear interaction of two shear waves. Next, imperfect conditions with different deviation angles are simulated and then demonstrated by experiments. The tolerable deviation of incident angle is also given based on the fitting curve obtained from simulations. Meanwhile, the measurements of the acoustic nonlinear parameter are performed on aluminum alloy, the Al7075-T6 specimens with different loading levels. The detection and localization of the plastic deformation based on the non-collinear wave mixing is also studied, whose results are then compared with the distribution of the plastic strain made by numerical simulations.

2. Theoretical considerations

2.1. Theoretical remarks

Non-collinear wave mixing was proposed by Jones and Kobett for the third-order elastic constants (TOECs) measurement [31], and experimentally observed by Rollins [32]. In the following work, only the case of the interaction of two shear waves is considered as shown in Fig. 1. The corresponding resonance condition is written as Eq. (1) [31]:

$$\left[\frac{2\pi f_1 + 2\pi f_2}{C_L}\right]\mathbf{r} - \mathbf{k}_1 - \mathbf{k}_2 = 0, \tag{1}$$

where $\mathbf{r}$ defines the propagation direction of the third longitudinal wave with a sum frequency of the two shear waves. f_1 and f_2 represent the frequencies of two primary shear waves respectively. $\mathbf{k}_1$ and $\mathbf{k}_2$ are the wave vectors of the two primary beams, respectively. C_L is the velocity of the longitudinal wave.

The interaction angle α of the non-collinear wave mixing can be determined by the calculation [31]:

Table 1
Material properties of aluminum applied for simulations.

ρ(kg/m^3)	λ(Pa)	μ(Pa)	l(Pa)	m(Pa)	n(Pa)
2700	5.1×10^{10}	2.6×10^{10}	-2.5×10^{11}	-3.3×10^{11}	-3.5×10^{11}

$$\cos\alpha = \frac{C_\mathrm{T}^2}{C_\mathrm{L}^2} + \frac{\left(\frac{C_\mathrm{T}^2}{C_\mathrm{L}^2} - \mathbf{1}\right)\left(\frac{f_1}{f_2} + \frac{f_2}{f_1}\right)}{\mathbf{2}}, \tag{2}$$

where C_T is the velocity of the shear wave. According to Eq. (2), it is known that the interaction angle is a function of the velocities and frequencies. The frequencies f_1 and f_2 are usually fixed in the measurements and so the deviation of an actual angle from the resonant angle will occur due to the variation of the exact velocities (C_T and C_L) in material. In addition, a tolerable deviation of incident angle is also needed for solving problems with unknown material properties or for problems where only estimates of material properties are available.

The model is simplified in which the frequencies of two primary waves are identical. The amplitude of the third longitudinal wave A_3 can be obtained by a series of calculations [31]:

$$A_3 = \frac{A_1 A_2 V \pi^2 f_1^3}{2\rho r}\left(\frac{1}{C_\mathrm{T}^4 C_\mathrm{L}}\right) \times \left[-\left(4uc^2 + nc^2\right) - \left(4K + u + 4m - n\right) \times \left(2c^4 - c^2\right)\right], \tag{3}$$

where A_1 and A_2 are amplitudes of two primary shear waves respectively, V is the volume of interaction, ρ is the material density, r is the propagation distance of the longitudinal wave, u is the shear modulus, c is the velocity ratio $C_\mathrm{T}/C_\mathrm{L}$. m and n are the Murnaghan constants, K is the compression modulus. It is noted that the amplitude of the new-generated longitudinal wave in Eq. (3) is inversely proportional to the propagation distance as the resonance wave is generated from a point source and propagates in a form of spherical wave. If considering the incidence of two plane shear waves, the amplitude of the third longitudinal wave A_3 will be independent of the propagation distance r if the attenuation or diffraction is neglected, which means r in Eq. (3) can be removed then.

The acoustic nonlinearity parameter χ is defined from Eq. (3) as:

$$\chi = \frac{A_3}{A_1 A_2}, \tag{4}$$

Based on Eq. (3) and Eq. (4), for the same excitation frequency and propagation distance, the χ is found to be dependent on the velocity of the longitudinal and shear wave, the third-order elastic constants (TOECs) of the material etc. In the early stage of material damage, the micro-damage state may lead to a variation of the TOECs and further may cause a change of the χ. According to the relationship between the material damage and the nonlinear ultrasonic feature, it is possible to use the acoustic nonlinearity parameter χ to evaluate the early-stage damage in materials or structures.

2.2. Numerical simulation details and employments

In this section, the non-collinear wave mixing was numerically studied using the commercial finite element software COMSOL to understand the effect of the incident angle deviations on the acoustic nonlinearity parameters. All the simulations were carried out using the TOECs model in an aluminum alloy, the elastic constants of which are listed in Table 1. The schematic of the wave mixing model is shown in Fig. 1. The thickness of the model was set as 15 mm and the incident angle was set as 59.5° based on Eq. (2). The left and right boundaries were set as absorbing ones.

Shear waves were excited by imposing tangential displacements on