



Evaluation of inherent and dislocation induced material nonlinearity in metallic plates using Lamb waves

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ABSTRACT

Previous studies carried out for quantifying the material nonlinearity of plate materials have used a nonlinearity parameter β which is derived for longitudinal waves. When Lamb waves are used as the probing waves, a relative nonlinearity parameter β' is used. This relative nonlinearity parameter β' is a non dimensionless parameter and gives the relative estimate of the material nonlinearity. In spite of these shortcomings, β' is widely used for quantifying the material nonlinearity using Lamb waves. Therefore, in the present study, firstly a physics based equation giving the nonlinearity parameter γ_{phy} in terms of higher order elastic constants is derived considering the Lamb wave motion. The parameter γ_{phy} gives an actual estimate of the material nonlinearity. This equation has its elastic component γ^e resulting from the lattice anharmonicity and plastic component γ^p resulting from the dislocations formed during fatigue or elastoplastic loading of the plate material. Secondly, a novel equation is derived to estimate the material nonlinearity γ_{amp} , which uses the amplitudes of the fundamental harmonic and second harmonic of Lamb waves generated because of the material nonlinearity. With the help of this equation, the actual inherent material nonlinearity can be estimated and it can also be used to quantify the density of dislocations once the amplitudes of the fundamental and second harmonics of Lamb waves in a specimen are made available from the experiments or simulation. Therefore, this equation is practically useful. In order to validate the model, a literature based experimental verification is used here. In the first part, the inherent material nonlinearities of two different materials are estimated and values of β' and γ_{amp} are compared qualitatively and quantitatively. In the second part, the density of dislocations is quantified using γ^p as well as γ^p/γ^e . The agreement of results among γ_{amp} and γ_{phy} for virgin as well as plastically loaded specimens, confirms the validity of the proposed models.

1. Introduction

The dislocation dipole substructures developed in a material during fatigue or elastoplastic loading makes the stress-strain relation of the material nonlinear. This material nonlinearity has been modelled theoretically in terms of a nonlinearity parameter β considering longitudinal wave motion in the material in Ref. [1]. In response to such material nonlinearity, a wave produces second harmonic and this phenomenon is modelled and correlated with β , both theoretically and experimentally using longitudinal waves in Ref. [1]. An inherent anharmonicity called as elastic nonlinearity in the material also gives rise to second harmonic in the wave, and β has been used in Ref. [2] to quantify this phenomenon. The value given by β is valid only for longitudinal waves. Thus, a different form of β called relative nonlinearity parameter β' is adopted in the literature [3–7] for estimating

material nonlinearity using other types of ultrasonic waves.

The higher harmonics generation is explored in the literature [8–12] using ultrasonic bulk waves to relate it with the changes happening in the dislocation density and persistent slip bands in the material just before the formation of microscopic cracks and that in the precipitate phase transformations during thermal aging [11,12]. However, in the case of plate structures, Lamb waves are used to assess the quality of plate material [7,13,14]. Nonlinear Lamb wave technology is mostly deployed for evaluating the microdamages in large structures, as these waves can travel sufficiently long distances with less attenuation and offer full cross-sectional coverage [15,16] as compared to the conventional point-by-point ultrasonic inspection. Deng and Pei [17] and Pruell et al. [5,18] correlated accumulated fatigue damage and plasticity driven material damage in metal plates with the higher harmonics produced in propagating Lamb waves. Matlack et al. [19] reviewed

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different models generating the second harmonic to evaluate states of the material such as plasticity, fatigue, thermal aging, and creep damage in metals. The dislocation monopole [20] and dipole [21] models are the basic theoretical models which explain generation of acoustic nonlinearity due to the dislocation substructures evolved during such states of the material. According to Hikata et al. [20] the oscillatory displacements of the monopole take place under the action of applied stress and nonlinear stress-strain relation, whereas, the nonlinear ultrasonic parameter estimated by Cantrell and Yost [21] based on the dipole model is independent of the applied stress. The dipole model proposed by Cantrell and Yost [21] is further processed by Cash and Cai [22] by considering the applied stress. However, Zhang and Xuan [23] found in their studies that in the model of Cash and Cai [22] the inverse signs between the stress-independent and stress-dependent terms of the acoustic nonlinearity may cancel out each other. Thus, Zhang and Xuan [23] modified the model of Cash and Cai [22] considering the precondition of identical signs of displacement and strain. However, these models have been used to estimate the material nonlinearity using longitudinal waves, wherein, stresses and strains are considered only along the direction of wave propagation. The present study uses Lamb waves for estimating material nonlinearity. Lamb wave has both longitudinal and transverse components which produce stresses and strains not only along the direction of wave propagation but also across it. Thus, in the present study, the basic dipole model of Cantrell and Yost [21] is modified to suit the purpose by considering additional stresses and strains across the wave direction.

The harmonics generated because of the nonlinearity of the supporting medium are desired to be cumulative with the propagation distance as they have very small amplitude and may subside easily. In order to have a cumulative effect, i.e. the amplitude of second harmonic to grow linearly with the propagation distance, certain conditions need to be met. Under this condition, second harmonic waves with measurable amplitude can be generated. A lot of researchers have theoretically studied the cumulative second harmonic generation in plate structures which include Muller [24], Matsuda and Biwa [25], De Lima and Hamilton [26], Chillara and Lissenden [27], Deng [28,29], etc. Deng [28,29] derived the conditions for second harmonic generation analytically. They showed that three conditions should hold for cumulative second harmonic generation in Lamb waves. Firstly, the power flux from the primary excited mode to the second harmonic mode is required. To ensure the power flux, the primary excited and second harmonics must have the same phase velocity. Considering small wave packets, group velocity matching of the primary excited and second harmonics, have to be the third condition.

Deng and Yang [30] and Bermes et al. [2] have worked on evaluating nonlinear state of pristine plate materials using higher harmonics produced in Lamb waves. Both the Refs. [30,2] used relative nonlinearity parameter β' adopted from the nonlinearity parameter β derived for the ultrasonic longitudinal waves, to characterize the plate material. The relation for β' is given as [2]

$$\beta' = \frac{A_2}{A_1^2}, \quad (1)$$

where A_1 and A_2 are amplitudes of the fundamental and second harmonics respectively. Another important thing to be noted here is that β' is not a dimensionless index. Although β' is successfully used by several researchers to characterize the plate material, it cannot give an actual estimate of the material nonlinearity. To the best of the authors knowledge, there is no amplitudes based equation available in the literature, which can give an actual estimate of the material nonlinearity considering Lamb wave motion in a plate.

In the present study, a theoretical benchmarking model for estimating the actual material nonlinearity is developed considering Lamb wave motion in the plate material. This physics based theoretical equation estimates the elastic γ^e and plastic γ^p components of the total nonlinearity parameter γ_{phy} . The elastic component is obtained from the

constitutive nonlinear stress-strain equation in terms of the higher order elastic constants, whereas, plastic component is obtained from the fundamental dislocation theory. Secondly, a novel amplitude based equation is derived which gives the value of material nonlinearity. This equation uses the amplitudes of the fundamental and second harmonics of Lamb waves obtained either through the experiments or simulation. In the case of virgin specimens, this equation can be used to estimate the inherent nonlinearity, whereas, for the in-service specimen, it can help quantify the degradation of specimens. The validation of the model is carried out for two different materials with distinct nonlinearities using the experimental data obtained from the literature. The values of β' and are estimated for a qualitative and quantitative comparison with γ_{phy} . The agreement among the results of γ_{phy} and confirms the validation and effectiveness of the proposed model. The organisation of paper follows the same sequence of activities as mentioned in this paragraph.

2. Physics based formulation of material nonlinearity parameter

The ultrasonic stress perturbation associated with propagating longitudinal waves produce only longitudinal strain component, whereas, Lamb waves produce both longitudinal as well as transverse strain components in the material. It is assumed that the total strain ϵ_T is the sum of elastic and plastic strain components ϵ_e and ϵ_p respectively associated with the motion of dislocations in the dipole configuration under the effect of propagating stress waves. Therefore,

$$\epsilon_T = \epsilon_e + \epsilon_p. \quad (2)$$

The total strain along the longitudinal and transverse directions can therefore be written as

$$\epsilon_T^x = \epsilon_e^x + \epsilon_p^x \quad \text{and} \quad \epsilon_T^y = \epsilon_e^y + \epsilon_p^y, \quad (3)$$

where x and y refer to the longitudinal and transverse directions respectively. In the case of a nonlinear material, the relations between stress perturbations and elastic strain components respectively in the longitudinal and transverse directions can be written as [1]

$$\sigma_x = A_2^e \epsilon_e^x + \frac{1}{2} A_3^e (\epsilon_e^x)^2 + \dots \quad \text{and} \quad \sigma_y = B_2^e \epsilon_e^y + \frac{1}{2} B_3^e (\epsilon_e^y)^2 + \dots, \quad (4)$$

where A_2^e, A_3^e and B_2^e, B_3^e are the Huang coefficients [1] in the longitudinal and transverse directions respectively.

The inverse form of Eq. (4) can be written as

$$\begin{aligned} \epsilon_e^x &= \left[\frac{1}{A_2^e} \right] \sigma_x - \frac{1}{2} \left[\frac{A_3^e}{(A_2^e)^3} \right] (\sigma_x)^2 + \dots \quad \text{and} \quad \epsilon_e^y \\ &= \left[\frac{1}{B_2^e} \right] \sigma_y - \frac{1}{2} \left[\frac{B_3^e}{(B_2^e)^3} \right] (\sigma_y)^2 + \dots. \end{aligned} \quad (5)$$

In the present work, the relation between acoustic stress perturbation and plastic strain ϵ_p is obtained from the consideration of dipolar forces. For edge dislocation pairs of opposite polarity, the shear forces F_x and F_y per unit length along the glide path on a given dislocation due to other dislocation in the pair, respectively in the longitudinal and transverse directions are given as [31]

$$F_x = -\frac{\mu(\mathbf{b}_x)^2}{2\pi(1-\nu)} \frac{x(x^2-y^2)}{(x^2+y^2)^2} \quad \text{and} \quad F_y = -\frac{\mu(\mathbf{b}_y)^2}{2\pi(1-\nu)} \frac{y(3x^2-y^2)}{(x^2+y^2)^2}, \quad (6)$$

where μ is the shear modulus, ν is the Poisson's ratio, and \mathbf{b}_x and \mathbf{b}_y are the Burger vectors in the longitudinal and transverse directions respectively. Under the condition of no residual stress, Eq. (6) asserts that $x = \pm y = \pm h$, where h is the dipole height. The effect of propagating Lamb waves along the slip planes causes the shear force per unit length $\mathbf{b}R\sigma$ on the dipole pair, where R is the Schmid factor [1]. In the equilibrium state, the total forces per unit length along the longitudinal and transverse directions respectively on the dipole can be written as $F_x + \mathbf{b}_x R \sigma_x = 0$ and $F_y + \mathbf{b}_y R \sigma_y = 0$. The relations between the plastic strain ϵ_p and relative dislocation displacement η , along the longitudinal

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