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A method to estimate the absolute ultrasonic nonlinearity parameter from relative measurements

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ABSTRACT

The ultrasonic nonlinearity parameter (β) is determined from the particle displacement amplitudes of the fundamental and second-order harmonic components in an ultrasonic wave propagated through a material. This parameter is generally referred to as the absolute parameter. However, measuring the second harmonic component is especially difficult because its amplitude is usually much smaller than those of signals in typical ultrasonic measurements. For this reason, most studies use the relative parameter determined using the measured electric signal amplitudes of the fundamental and second harmonic ultrasonic waves. However, in many occasions, the absolute parameter is needed for a quantitative assessment of material degradation. This study proposes a method to estimate the absolute parameter from a measured relative parameter along with a proportionality constant between normalized absolute and relative parameters. This method is based on the observed fact that the ratio of between normalized relative and absolute parameters is identical after compensating proportionality constant. The method was experimentally validated for Al6061-T6 alloy specimens heat-treated for different aging times. The parameter determined through the proposed method were compared with the absolute parameters which were measured separately. The results show that these two parameters were close to each other within the measurement errors.

1. Introduction

Nonlinear ultrasonic techniques (NUT) have been considered a promising nondestructive method to evaluate the variations in the nonlinear elastic property induced by material degradation. This technique is based on the nonlinear elastic interaction between a material and a propagating ultrasonic wave. One of the most widely used phenomena is the higher order harmonics generation in the propagating ultrasonic waves. A monochromatic ultrasonic wave transmitted into the material is distorted during propagation causing higher-order harmonic components to be generated. The amplitudes of these higher-order harmonic components depend on the nonlinear elasticity of the material. Thus, in NUT, the amplitudes of the higher-order harmonic components after propagation are measured, which can in turn be used to evaluate elastic nonlinearity which is more sensitive to material degradation than linear elastic property.

Traditionally, the ultrasonic nonlinearity parameter (β) which is defined by the ratio of the displacement amplitude of the second-order harmonic component and the square of the displacement amplitude of the fundamental frequency component, has been used to evaluate the elastic nonlinearity. It is generally referred to as the absolute parameter. This parameter is closely related to microstructural changes such as precipitates [1] and dislocations [2–4].

However, only a few techniques to measure the absolute parameter are available. Well-known methods include capacitive detection [5], laser interferometry [6], and piezo-electric detection [7,8]. Among these methods, capacitive detection and laser interferometry are severely affected by the surface roughness of the material. On the other hand, the piezo-electric detection [7,8] is less affected by the material surface roughness and furthermore, uses general ultrasonic nondestructive testing equipment such as piezo-electric transducers and ultrasonic wave generator; thus, this method is rather convenient compared to the others. Despite these advantages, the piezo-electric detection is not practical due to the inconvenience of additional processes required for the calibration. Therefore, most studies have been limited to the measurement of the relative parameter (β') which is defined by the

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detected signal amplitude regardless of displacement or not, as it is easier and more convenient to measure. The relative parameter is useful to track a relative change of the nonlinearity before and after a material degradation such as creep [9], fatigue [10], and thermal aging [11–13]. However, the absolute parameter is needed for the quantitative assessment of the material degradation.

This study proposes a method to estimate the absolute parameter for damaged materials based on the relative parameter along with a proportionality constant between normalized absolute and relative parameters. This method is based on the finding that the ratio of between normalized relative and absolute parameters is identical after compensating for the material dependent proportionality constant such as the wavenumber and the detection-sensitivity [14]. In the case where the degradation of a given material is monitored, the absolute parameter after a certain exposure time (β) can be estimated from the relative parameter at that time normalized by the initial relative parameter (β'/β'_0) and the initial absolute parameter (β_0). In this case, the proportionality constant (wavenumber ration times the detection-sensitivity ratio) is very close to unity.

In order to experimentally validate the feasibility of the proposed method, the Al6061-T6 alloy specimens were heat-treated at a constant temperature of 220 °C with different aging times (0, 60, 120, 600, 6000, and 60,000 min). Both the relative and the absolute parameters were measured separately for all specimens. The piezo-electric detection was employed to measure the absolute parameter. The absolute parameters estimated by the proposed method were then compared to the directly measured absolute parameters.

2. Ultrasonic nonlinearity parameter

To measure the ultrasonic nonlinearity parameter, a finite amplitude monochromatic ultrasonic signal is transmitted into a material and then the signal is detected after propagating through the material. The propagating ultrasonic wave is distorted by nonlinear interaction with the material, which may lead to the generation of second-order harmonic components. The nonlinearity parameter (β) is determined from the displacement amplitudes of the fundamental and the second-order harmonic frequency components as follows [15,16]:

$$\beta = \frac{8A_2}{k^2 x A_1^2} \tag{1}$$

where A_1 and A_2 are the displacement amplitudes of the fundamental and second-order harmonic components, k is the wavenumber, and x is the wave propagation distance. This parameter (β) is referred to as the absolute parameter.

On the other hand, the relative parameter (β') is defined as follows:

$$\beta' = \frac{A'_2}{A'^2_1} \tag{2}$$

where A'_1 and A'_2 are the detected signal amplitudes for the fundamental and second-order harmonic wave, which are not restricted to the displacement amplitude. Therefore, the relative parameter can be measured by using the voltage output signal detected by a conventional piezo-electric transducer. Note that when we measure the relative parameter (β') the measurement conditions, such as the equipment, frequency, and thickness of specimen, should all be kept constant. Although the relative parameter is different from the absolute parameter, it can be used for a relative comparison of nonlinearity between different materials. However, the absolute parameter is still needed for a quantitative assessment of material degradation.

3. Relationship between absolute and relative parameters

Here, a theoretical relationship between the absolute and relative parameters is deduced. First, it is assumed that the detected signal amplitudesA'_1 and A'_2 are linearly proportional to the actual displacement amplitudes A_1 and A_2 respectively, as follows [15]:

$$\begin{aligned} A_1 &= A'_1 \cdot \alpha_1 \\ A_2 &= A'_2 \cdot \alpha_2 \end{aligned} \tag{3}$$

where α_i is the displacement-proportionality coefficient ($i = 1$ for the fundamental frequency and $i = 2$ for the second-order harmonic frequency) of the detected signal amplitude, which is related to the frequency-dependent sensitivity of the transducer (i.e., the efficiency of acoustic energy conversion into electrical energy). Since the piezo-electric transducers produce a voltage output proportional to the displacement of an acoustic wave at a fixed frequency, the above assumption is reasonable for piezo-electric transducers. The influences of attenuation and diffraction were neglected.

Next, let us consider the ratio of the nonlinearity parameter between the reference material and the test material, assuming that the propagation distance x is constant. For this Eq. (3) is substituted into Eq. (1), and the definition of β^{prime} in Eq. (2) is used to derive the following [14]:

$$\frac{\beta}{\beta_0} = \frac{\frac{1}{k} \cdot \frac{A_2}{A_1^2}}{\frac{1}{k_0} \cdot \frac{A_{2,0}}{A_{1,0}^2}} = \frac{\frac{1}{k} \cdot \frac{\alpha_1 \cdot A'_2}{\alpha_1^2 \cdot A'^2_1}}{\frac{1}{k_0} \cdot \frac{\alpha_{2,0} \cdot A'_{2,0}}{\alpha_{1,0}^2 \cdot A'^2_{1,0}}} = k' \cdot \alpha' \cdot \frac{\frac{A'_2}{A'^2_1}}{\frac{A'_{2,0}}{A'^2_{1,0}}} = k' \cdot \alpha' \cdot \frac{\beta'}{\beta'_0} \tag{4}$$

where k' is the wavenumber ratio, α' is the displacement-proportionality ratio (affected by the detection-sensitivity of the two materials), while the subscript "0" indicates the value for the reference material. When we compare the nonlinearity parameter before and after the damage in the same kinds of materials, the wavenumbers and the detection-sensitivities are similar and therefore k' and α' can be regarded as unity in general. Of course, if k and α are dramatically changed before and after damage they should be compensated for. When k' and α' can be neglected Eq. (4) is simplified as follows [15]:

$$\frac{\beta}{\beta_0} = \frac{\beta'}{\beta'_0} \tag{5}$$

In this case, the ratio of the relative parameters between the intact and damaged material is identical to that of the absolute parameters, and the quantitative ratio of the absolute parameters can be obtained simply by measuring the relative parameters. From this, the absolute parameter of the damaged material can be represented as follows:

$$\beta = \frac{\beta'}{\beta'_0} \times \beta_0 \tag{6}$$

Therefore, when we know the absolute parameter of a material in intact condition, the absolute parameter of the material after damage can be obtained by measuring the ratio of the relative parameters. In order to apply this method to the health monitoring of a material in operation, we have to preserve an intact specimen of same material and measure the relative parameters of both the material in operation and the intact specimen. As mentioned previously, when measuring the ratio of relative parameters between different test materials, it is important to keep the measurement condition consistent. Thus, it is preferred that the relative parameter of the intact specimen is measured each time the relative parameter of the material in operation is measured.

In this study, estimated value of β is defined by Eq. (6) as β_e.