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Combination of nonlinear ultrasonics and guided wave tomography for imaging the micro-defects

Weibin Li [a], Younho Cho [b,*]

[a] Department of Aeronautics, Xiamen University, 422, South Siming Road, 361005 Xiamen, China
[b] School of Mechanical Engineering, Pusan National University, 10511, San 30, Jangjeon-dong, Geumjeong-gu, 609-735 Busan, South Korea

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ABSTRACT

The use of guided wave tomography has become an attractive alternative to convert ultrasonic wave raw data to visualized results for quantitative signal interpretation. For more accurate life prediction and efficient management strategies for critical structural components, there is a demand of imaging micro-damages in early stage. However, there is rarely investigation on guided wave tomographic imaging of micro-defects. One of the reasons for this might be that it becomes challenging to monitor tiny signal difference coefficient in a reliable manner for wave propagation in the specimens with micro-damages. Nonlinear acoustic signal whose frequency differs from that of the input signal can be found in the specimens with micro-damages. Therefore, the combination of guided wave tomography and nonlinear acoustic response induced by micro-damages could be a feasibility study for imaging micro-damages. In this paper, the nonlinear Rayleigh surface wave tomographic method is investigated to locate and size micro-corrosive defect region in an isotropic solid media. The variations of acoustic nonlinear responses of ultrasonic waves in the specimens with and without defects are used in guided wave tomographic algorithm to construct the images. The comparisons between images obtained by experimental signals and real defect region induced by hydrogen corrosion are presented in this paper. Results show that the images of defect regions with different shape, size and location are successfully obtained by this novel technique, while there is no visualized result constructed by conventional linear ultrasonic tomographic one. The present approach shows a potential for inspecting, locating and imaging micro-defects by nonlinear Rayleigh surface wave tomography.

1. Introduction

The use of nonlinear ultrasonic waves has been proposed as a potential method for detecting micro-defects to which linear ultrasonic methods are less sensitive [1–4]. Recently, nonlinear ultrasonic approaches have been reported in numerous studies to assess material micro-damage [5,6] and characterize material degradation [7,8], respectively. Since the energy of Rayleigh surface waves is concentrated near the surface, these waves are taken as an efficient tool for non-destructive evaluation (NDE) of damages that initiates at the material surface [9]. Additional advantages of Rayleigh surface waves include longer propagation distance than for conventional bulk waves to interrogate large, complex components where is not accessible for visual inspection. Considering the high sensitivity of nonlinear ultrasonic method and the great advantages of surface guided wave approach, nonlinear ultrasonic surface wave technique has drawn significant attention for nondestructive evaluation of damages in early stages [10–12].

Another remarkable progress of ultrasonic wave NDE is an imaging potential over a hidden or inaccessible damage zone. One of the effective ways to quantitatively monitor a structure is to obtain the images via either scanning or tomography [13]. There have been a number of different tomographic schemes, and some of the most well-known methods are time-difference-of-arrival imaging method, energy arrival and the reconstruction algorithm for the probabilistic inspection of damage (RAPID) method [14–16]. The RAPID based tomographic approach is apt to be implemented efficiently with ultrasonic guided wave features. The major advantage of using RAPID algorithm is the simplicity in the data interpretation, that the wave diffraction is accounted only on the line of propagation path with the linear interpolation of defect location probability distribution [17]. However, to authors' knowledge, most of earlier efforts of guided wave tomographic techniques have been limited to the use of linear features

* Corresponding author.
E-mail address: mechcyh@pusan.ac.kr (Y. Cho).

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of time domain wave signals for imaging macro-damages. There is rarely investigation on nonlinear guided wave tomographic imaging of micro-defects. One of the reasons for this might be that it becomes challenging to monitor tiny signal difference coefficient in a reliable manner for wave propagation in the specimens with micro-damages. Recently, Solodov and Busse [18] reported the application of local defect resonance concept enhances substantially the efficiency of vibro-thermal conversion in ultrasonic thermography for resonance ultrasonic thermography for imaging contact crack. Solodov and Busse [19] and Eren et al. [20] developed experimental methodologies of nonlinear scanning laser vibrometry and nonlinear air-coupled emission to study the interactions of nonlinear elastic wave and defects for defect-selective imaging of closed cracks. It has verified the higher sensitivity and resolution of imaging micro-damages by acoustic nonlinear response [21].

In this paper, nonlinear Rayleigh surface wave tomographic technique, is investigated to locate and size micro-corrosive defect region in an isotropic solid media. Instead of extracting the linear features from a time domain wave signal, the nonlinear acoustic signal in frequency domain which caused by the frequency conversion of Rayleigh surface wave signals is used in the modified tomographic algorithm. Nonlinear parameter of Rayleigh surface wave propagation in an isotropic medium is derived to express the nonlinear feature of surface waves. A modified RAPID tomographic algorithm is developed to construct the images of various defects in aluminum plates. The tomographic images of artificial chemical corrosive defect regions in the specimens are reconstructed by combining acoustic nonlinear response with the modified guided wave tomography. The proposed technique shows a potential for inspecting, locating and imaging micro-defects by nonlinear Rayleigh surface wave tomography.

2. Theory

2.1. Nonlinear surface wave

Rayleigh surface wave propagates in a positive x direction, while z axis points into the half-space as shown in Fig. 1. According to partial wave techniques, the displacement of Rayleigh surface wave propagating in an isotropic half-space with traction-free boundary condition could be decomposed into in-plane and out-of-plane contributions [9,10,12,22–24].

The displacement potentials that describe the longitudinal and shear waves are written as,

$$u = \frac{\partial \phi}{\partial x} - \frac{\partial \varphi}{\partial z}, \tag{1}$$

$$w = \frac{\partial \phi}{\partial z} + \frac{\partial \varphi}{\partial x}, \tag{2}$$

$$\phi = \frac{A}{ik} e^{-pz} e^{i(kx-wt)}, \tag{3}$$

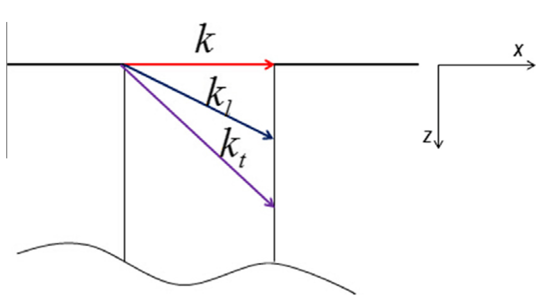

Fig. 1. Surface wave propagation along x direction.

$$\varphi = \frac{B}{ik} e^{-qz} e^{i(kx-wt)}, \tag{4}$$

where $p^2 = k^2 - k_l^2$, $q^2 = k^2 - k_t^2$, and k, k_l and k_t are the wave number for surface wave, longitudinal wave and transverse wave, respectively. w is angle frequency. The stress free boundary conditions demand that the stresses σ_{zz} and σ_{xz} go to zero on the surface ($z = 0$). The constants A and B are related by

$$B = -iA \frac{2kp}{k^2 + q^2}. \tag{5}$$

Partial wave technique and normal modal expanding method are used to analyze the amplitude relation of fundamental wave and second harmonic wave displacement [22,25]. On the surface, the Rayleigh surface wave can be decomposed into the cross-interaction and self-interaction of longitudinal and shear wave components. So the displacement components of fundamental frequency wave and second harmonic surface waves on the surface can be represented as

$$u(f) = A\left(e^{-pz} - \frac{2pq}{k^2+q^2} e^{-qz}\right) e^{i(kx-wt)}, \tag{6}$$

$$w(f) = iA\frac{p}{k}\left(e^{-pz} - \frac{2k^2}{k^2+q^2} e^{-qz}\right) e^{i(kx-wt)}, \tag{7}$$

$$u(2f) = D\left(e^{-2pz} - \frac{2pq}{k^2+q^2} e^{-2qz}\right) e^{-i2wt}, \tag{8}$$

$$w(2f) = iD\frac{p}{k}\left(e^{-2pz} - \frac{2k^2}{k^2+q^2} e^{-2qz}\right) e^{-i2wt}. \tag{9}$$

The second harmonic field can be described as,

$$D = \sum_{n=1}^{3} C^{(n)} e^{ik^{(n)}x}, \tag{10}$$

where

$$C^{(1)} = -\left(\frac{3\rho c_l^2 + C_{111}}{8\rho c_l^2}\right) k_l^2 A^2 x, \quad k^{(1)} = 2k_l. \tag{11}$$

$$C^{(2)} = -\left(\frac{\rho c_l^2 + C_{166}}{4\rho c_l^2}\right) \frac{k_t^3 A^2}{(k_t^2 - k_l^2)} \sin[(k_t - k_l)x], \quad k^{(2)} = k_l + k_t. \tag{12}$$

$$C^{(3)} = -\left(\frac{\rho c_l^2 + C_{166}}{\rho c_t^2}\right) \frac{(k_l k_t^2 + k_t k_l^2)A^2}{(k_l + k_t)^2 - 4k_t^2} \sin\left[\left(\frac{k_t - k_l}{2}\right)x\right],$$
$$k^{(3)} = \frac{3k_t + k_l}{2}. \tag{13}$$

It is found that $C^{(2)}$ and $C^{(3)}$ will vanish at a certain propagation distance, which means these two components have no accumulative contributions to second harmonic Rayleigh surface wave filed. It assumed that wave propagation distance is sufficiently long, so the second harmonic field could be mainly attributed to $C^{(1)}$. From above analysis, it is found that the relationship between D and A on the surface can be expressed as

$$D = \frac{\beta_l k_l^2 A^2 x}{8} e^{i2kx}, \tag{14}$$

where $\beta_l = -\frac{3\rho c_l^2 + C_{111}}{8\rho c_l^2}$ is the acoustic nonlinearity parameter for longitudinal wave; x is wave propagation distance. The similar results can also be found in [10]. Generally, the out-of-plane displacement