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A novel approach to surface defect detection

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ABSTRACT

Defects or flaws in highly loaded structures have a significant impact on the structural integrity. Early inspection of faults can reduce the likelihood of occurrence of potential disasters and limit the damaging effects of destructions. According to our previous work, a novel approach called as Quantitative Detection of Fourier Transform (QDFT) using guided ultrasonic waves is developed in this paper for efficiently detecting defects in pipeline structures. Details of this fast method consist of three steps: First, an in-house finite element code has been developed to calculate reflection coefficients of guided waves travelling in the pipe. Then, based on boundary integral equations and Fourier transform of space-wavenumber domain, theoretical formulations of the quantitative detection are derived as a function of wavenumber using Born approximation. This lays a solid foundation for QDFT method, in which a reference model in a problem with a known defect is utilized to effectively evaluate the unknown defects. Finally, the location and shape of the unknown defect are reconstructed using signal processing for noise removal. Several examples are presented to demonstrate the correctness and efficiency of the proposed methodology. It is concluded that the general two-dimensional surface defects can be detected with high level of accuracy by this fast approach.

1. Introduction

Quantitative detection of defects in elastic solid is always a hot research topic, and how to precisely determine the defect location and shape is the focus. Early in the ultrasonic inspection, the diffraction tomography (Blackledge, Burge, Hopcraft, & Wombel, 1987a; Devaney, 1984) of the scalar fields was applied, based on full-space Green's function and the equation of scatter fields, to inspect defects in solid, where locations of the source and receiver were different. Subsequently, Blackledge, Burge, Hopcraft, and Wombel (1987b) used quantitative diffraction tomography of elastic waves to reconstruct two-dimensional defects. The tomography methods reconstruction was also applied to inspect concrete structures with and without reinforcement (Chang, Peng, & Liu, 2018). In order to reduce the costs of samplings and experiments, and enhance the image resolution, many researchers (Batenburg & Sijbers, 2011; Laroque, Sidky, & Pan, 2008; Sheppard & Shan, 2010) proposed different algorithms to improve diffraction tomography. In the inverse problems, other approaches were given, which were suitable for different models, such as eddy current methods (Dobson & Santosa, 1998), time reversal (Minnaar & Zhou, 2004) and modal power flow (Wang et al., 2008).

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Recently, ultrasonic guided waves have been also used to detect defects, because they are more suitable and effective for large structures inspection. For plate-like structures, Leonard, Malyarenko, and Hinders (2002) applied tomographic reconstruction for nondestructive evaluation (NDE) of aerospace structures. Huthwaite and Simonetti (2013) and Huthwaite (2014) compared the ray tomography and diffraction tomography techniques, and provided a mechanism to determine the thickness from a velocity reconstruction. Jing, Ratassepp, and Zheng (2017) showed accurate reconstruction of guided wave tomography using full waveform inversion and Hosoya, Yoshinaga, Kanda, and Kajiwara (2018) proposed a non-contact, non-destructive method to generate Lamb waves by laser-induced plasma.

It is challenging work to consider defect inspection in pipeline structures due to the difficulty of extracting singe mode from multiple modes of waves. How to excite useful guided waves in pipelines by experiments is the first step during the process of detecting pipes. Ditri and Rose (1992) applied surface tractions and the normal mode expansion technique to excite guided waves in hollow cylinders. The flexible PVDF pipe comb transducers were designed (Hay & Rose, 2002), which can enhance axial displacements and reduce radial displacements. Liu, He, Wu, Wang, and Yang (2006) utilized thickness shear mode piezoelectric elements to excite T(0,1) mode. In the meanwhile, numerical calculations were performed to simulate scattering fields by many researchers. A combination of finite element formulation and wave function expansion were employed to investigate the scattering of axisymmetric guided waves (Rattanawangcharoen, Zhuang, Shah, & Datta, 1997). Duan and Kirby (2015) applied a weighted residual formulation to deliver an efficient hybrid numerical formulation. Mountassir, Yaacoubi, Mourot, and Maquin (2018) suggested a Structural Health Monitoring (SHM) method for damage detection and localization in pipeline by calculating a sparse estimation of the current signal. To further apply guided waves for defect inspection in pipes, several detecting methods have been proposed. By frequency bandpass filters and wavelet analysis, Siqueira, Gatts, da Silva, and Rebello (2004) processed ultrasonic signals with a low signal/noise ratio acquired with a single transducer in an pulse-echo configuration. Stoyko, Popplewell, and Shah (2014) found dispersive guided waves can be used to detect a notch in pipes due to the difference of the cutoff frequencies between undamaged pipes and damaged pipes. Employing a circumferentially distributed phased array, guided wave focusing techniques (Mu, Zhang, & Rose, 2007) were used to detect axial and circumferential location, which improved penetration power and circumferential resolution. An ant colony classification model was proposed to detect structural defects in piles by evaluating displacement–time plots to improve the reliability of pile monitoring (Psychas et al., 2016).

In this paper, we adopt reflection coefficients in full wavenumber domain to reconstruct the pipes' defects using boundary integral equation of ultrasonic waves. To improve surface defect detection, an in-house hybrid finite element (FE) code is developed to efficiently calculate reflection coefficients in scattering fields. Following this, a new approach, called as Quantitative Detection of Fourier Transform (QDFT), is proposed for reconstruction of defects with high level of accuracy and efficiency. The procedure of QDFT for defect detection consists of three steps: first, Fourier transform is applied to convert the shape function $\eta_0(x)$ of a known defect into a wavenumber domain function $H_0(k)$. Then, reflection wave coefficients $C_0(k)$ are calculated by hybrid FEM. Based on boundary integral equation, the term $B(k)$, which only depends on wavenumbers for a given thickness of the structure, is approximately obtained from the reference model. Finally, employing inverse Fourier transform, the real defect $\eta(x)$ is reconstructed. It is noted that the general two-dimensional surface defects can be detected with high level of accuracy by the developed QDFT.

2. Brief review of boundary integral equations for scattering problems

According to reciprocal theorem (Schmerr, 1998), the integral equation of total fields in Cartesian coordinate system is written as:

$$\int_S \left[u_i^{\text{total}}(\boldsymbol{x})T_{ij}^{\alpha}(\boldsymbol{x}-\boldsymbol{X}) - U_i^{\alpha}(\boldsymbol{x}-\boldsymbol{X})\sigma_{ij}^{\text{total}}(\boldsymbol{x})\right]\boldsymbol{n}_j dS(\boldsymbol{x}) = u_{\alpha}^{\text{sca}}(\boldsymbol{X}) \qquad i, j, \alpha = 1, 2 \quad \boldsymbol{X} \notin V \tag{1}$$

where the field point and source point are defined by the coordinates (x_1, x_2) and (X_1, X_2), respectively. The superscripts 'total' and 'sca' mean total fields and scatter fields, $T_{ij}^{\alpha}(\boldsymbol{x}-\boldsymbol{X})$ and $U_i^{\alpha}(\boldsymbol{x}-\boldsymbol{X})$ represent full-space Green's functions of stresses and displacements, α is the direction of a unit load in Green's function, $u_i^{\text{total}}(\boldsymbol{x})$ and $\sigma_{ij}^{\text{total}}(\boldsymbol{x})$ are displacements and stresses, $\boldsymbol{n}_j$ denotes the normal vector of the defect boundary $S(\boldsymbol{x})$, and 'V' depicts the defect area. Considering the traction-free boundary condition and Green's function $\tilde{T}_{ij}^{\alpha}(\boldsymbol{x}-\boldsymbol{X})$ of the structure, displacements in scatter fields can be written as:

$$\int_S \left[u_i^{\text{total}}(\boldsymbol{x})\tilde{T}_{ij}^{\alpha}(\boldsymbol{x}-\boldsymbol{X})\right]\boldsymbol{n}_j dS(\boldsymbol{x}) = u_{\alpha}^{\text{sca}}(\boldsymbol{X}) \ \boldsymbol{X} \notin V \tag{2}$$

In light of Gauss's divergence theorem, Eq. (2) can be further defined as

$$\int_{-\infty}^{+\infty} e^{-2i\xi x_2} e^{i\xi X_2} \int_{h-h_n(x_2)-\eta(x_2)}^{h} \left[A_i^{\text{inc}}(x_1)\tilde{P}_{ij}^{\alpha}(x_1 - X_1)\right]_{,j} dx_1 dx_2 = u_{\alpha}^{\text{sca}}(\boldsymbol{X}) \tag{3}$$

where ξ denotes wavenumber, the subscript ', j' denotes $\frac{\partial}{\partial x_j}$, $\tilde{T}_{ij}^{\alpha}(\boldsymbol{x}-\boldsymbol{X}) = \tilde{P}_{ij}^{\alpha}(x_1 - X_1)e^{-i\xi(x_2 - X_2)}$, h and $\eta(x_2)$ signify the structure thickness and defect depth, respectively. According to Born approximation, the total fields can be approximately replaced by the incident fields. Therefore, $A_i^{\text{total}}(x_1) \approx A_i^{\text{inc}}(x_1)$, $u_i^{\text{total}}(x) \approx A_i^{\text{inc}}(x_1)e^{-i\xi x_2}$, and $\eta(x_2) \to 0$ if the defect is small. The incident and reflected waves with the same mode of the guided wave are written as $u_{\alpha}^{\text{inc}}(X) = A_{\alpha}^{\text{inc}}(X_1)e^{-i\xi X_2}$ and $u_{\alpha}^{\text{ref}}(X) = A_{\alpha}^{\text{ref}}(X_1)e^{i\xi X_2}$.