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A REGULARIZATION TECHNIQUE FOR QUANTITATIVE IMAGING OF CORROSION IN PIPELINES

Min Lin[1], Casey Smith[1], Jing Rao[2], Zheng Fan[2], Yang Liu[1, 3]
[1]Department of Mechanical Engineering, University of Wyoming, Laramie, WY
[2]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore
[3]Schlumberger-Doll Research, Cambridge, MA

ABSTRACT

Corrosion is a major economic and safety issue in the oil and gas industry. Oil and gas pipelines have severe corrosion problems, which cost the industry billions of dollars per year. Guided wave tomography (GWI) provides great prospects to estimate the remaining thickness of corrosion structures. A quantitative corrosion imaging method is presented for pipeline structures, which is not only able to locate the position of corrosion damage precisely but also determine the depth profile. The reconstruction of the thickness map can be obtained by using the dispersion characteristics of ultrasonic guided waves and the algorithm based on full waveform inversion (FWI). A limited view regularization technique is applied to the limited view problems. Two transducer arrays are arranged on each side of the detection area, thus limiting the viewing angles. The missing angles cause artifacts and reduced the tomography quality. Both FEA numerical simulations and experiments are conducted on one regularly shaped defect and two irregularly shaped defects. FWI with limited view regularization shows accurate predictions of corrosion position and depth profile.

Keywords: full waveform inversion, corrosion, limited-view regularization

1. INTRODUCTION

Corrosion has been one of the significant problems of pipelines in the oil and gas industry. Huge amount of money is spent every year on the maintenance of pipelines as a result of corrosion. Corrosion is also the leading cause of severe pipeline accidents. For these reasons, it's essential to have a deep understanding of corrosion phenomena and develop strategies to detect the wall thickness loss due to corrosion in early stages.

Guided wave tomography provides great prospects to inspect and quantify the loss of pipeline thickness. Traditional thickness measuring methods use an ultrasonic thickness gauge for the non-destructive testing of structure's thickness. This method can obtain high accuracy and be easily deployed without laboratory conditions. However it is tedious and expensive, particularly for these insulated defects that are hard to access. Guided wave tomography technique offers a more efficient and reliable way to monitor the remaining thickness of corrosion position without probing all points on the surface. The method is based on the dispersion characteristic of particular modes, and thickness profile can be obtained by converting the reconstructed velocity map. An accurate reconstruction can be obtained from the measurement with full view configuration. However, for the detection of pipelines, two transducer arrays are usually placed at both ends of the detection area, which limits the viewing angles. As a result of the limited view, these missing angles will lead to remarkable artifacts and deteriorate the quality of reconstruction features. Recently, Rao introduced the adjustable thresholding regularization approach in the full waveform inversion algorithm to reconstruct the thickness map of plates with limited view configuration. In our research, a regularization technique based on full waveform inversion algorithm are developed to improve the reconstruction of the thickness profile of pipelines, which has been shown as an accurate prediction of the remaining thickness.

2. MATERIALS AND METHODS

2.1 The limited view problem and regularization

With the assumption of far field, a Born model is used to analyze the limited view problem. The scattering field U_s under Born approximation is given by

$$U_s \approx -\int_{\Omega} e^{ik(\hat{s}_0-\hat{s})x} O(x)dx\,, \tag{1}$$

where Ω is the domain of the scatter and k is the wavenumber. $\hat{s}_0$ is the direction of the incident illumination and $\hat{s}$ points towards the receiver. $O(x)$ is the object function. Using a Fourier transform of the object function O, which leads to

$$U_s(\hat{s}_0, \hat{s}) \approx -\tilde{O}[k(\hat{s}_0-\hat{s})]. \tag{2}$$

[1] Contact author: yliu19@uwyo.edu

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This means that the signal from each source-receive pair corresponds to the Fourier component of the object function at $k(\hat{s}_0 - \hat{s})$. In the limited view problem, the illumination and reception angles are restricted. Only the information of the limited sections can be obtained from the measurements. The main challenge of the limited view problem is how to reconstruct the limited view imaging when there is only a limited number of Fourier components available. One solution to the problem is to set the unknown k-space components to zero, which lead to a low-pass filtered version of the true image. Then, by changing the negative values to zero, the image with addition information is obtained after the forward Fourier transform. Another solution is to apply the adaptive thresholding regularization method. In many situations, the peak features can be relatively reconstructed, but the lower amplitude features can't. According to this characteristic, a threshold is applied to the image, which will increase the unmeasurable components. The extra information can be acquired by applying this method. The threshold can be defined as

$$\begin{cases} m(x) & if \ \dfrac{|m(x) - m_0|}{\max|m(x) - m_0|} < l_e \\ m_0 & \text{otherwise} \end{cases}, \tag{3}$$

where $m(x)$ and m_0 are the model parameter at x and the level of the background, respectively, and l_e is the threshold function.

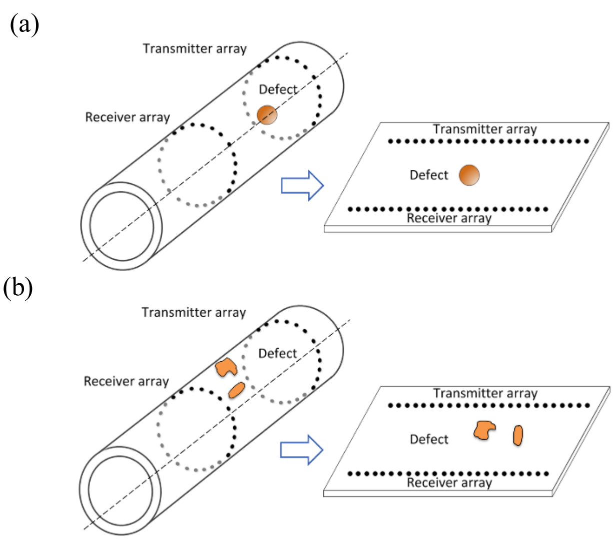

FIGURE 1: The schematic of (a) one hemispherical defect with radius of 2 mm, and (b) two irregularly shaped flat bottom defects having the depth of 1 mm and 1.5 mm, respectively, on the surface of the pipeline

2.2 Validation Methods

In this research, two kinds of defects, regularly shaped defect and irregularly shaped ones, on the surface of half-scale stainless steel pipes with the dimension of 3.50" OD and 0.188" wall thickness are studied in both 3D finite element simulations and experiments to validate the accuracy of the method. As shown in figure 1, the regularly shaped defect is a hemispherical defect with radius of 2 mm, and irregularly shaped defects are two flat bottom defects having the depth of 1 mm and 1.5 mm, respectively. A 5 circle Hanning-windowed tone-burst signal was generated as the input signal. In FE simulations, absorbing layers were applied to eliminate the reflection effect from the boundaries. To avoid reflections from pipe edges in the experiments, only transmitted signals were measured.

3. RESULTS AND DISCUSSION

For one defect case, three sequential frequencies of 35, 46, and 60 kHz were used in the standard limited view FWI algorithm, with 40 iterations per frequency. Compared to the full view configuration, distortion of the defect happens in the case with limited viewing angles, but the quality of the resolvable area is not degraded. The artifacts are significantly reduced by applying the regularization method. Both the depth profile and position of the defect are well reconstructed.

As for two defects case, following the same frequencies and the iteration number. The image only includes the information of the larger defect with little information of the shallow defect in the first regularization. After several iterations of regularization with increasing threshold level, both defects are clearly reconstructed. But the size of the shallower defects seem to be smaller due to the under-sampling of the wave field.

4. CONCLUSION

The research has developed the regularization method in the full waveform inversion algorithm to locate the corrosion positions and predict the thickness maps of pipelines with limited view configuration. Both FEA simulations and experiments were conducted to validate the accuracy of this method. The results showed that the quality of reconstruction image is improved through integrating the measured data and the additional information from the regularization technique. The reconstruction of the thickness map of the pipe elbow can be studied by using the regularization method in the future work.

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