Steps for Characterizing Crack-Like Defects in Real-World Hollow Cylindrical Structures from Scattering of Helically Guided Ultrasonic Waves

---

P. SHIVASHANKAR, JUNGHOON SOHN, NATHAN WILSON,
GUAN-WEI LEE and SALVATORE SALAMONE

ABSTRACT

Recently, a method called the stepped wavelength scattering analysis was proposed for tracking the growth of circumferential crack-like defects in hollow cylindrical structures. As the name implies, this method is based on the scattering of helical guided ultrasonic waves (HGUW). To identify the defect length, the method quantifies the perceivable change in the nature of interactions as the wavelength-to-crack length ratio goes from being less than one to equal to or greater than one. Specifically, when the wavelength is smaller than the defect size, the scattering directivity plots are well-explainable by *ray-like* interactions. However, when the wavelength becomes comparable or greater than the defect size, the interaction is *diffraction-dominated*. This change in scattering pattern with respect to wavelength-to-crack length was quantified to establish a criterion for estimating the defect length. Building on this foundation, this paper discusses the steps for extending the method for practical implementation in real-world structures. As such, a three-step strategy with circumferential arrays of transducers is proposed. The steps include (1) locating the defect through HGUW tomography, (2) estimating its orientation from the angular distribution of scattered lobes, and (3) determining its length using the stepped-wavelength scattering analysis. The discussion also highlights a key requirement for implementation: reconstructing full circular-array responses from circumferential measurements. Once a DNN-based model is developed to accomplish this, the proposed three-step framework can enable practical in-situ monitoring and tracking of crack-like defects in hollow cylindrical structures.

INTRODUCTION

Hollow cylindrical structures form an essential part of several critical infrastructures. Structures and systems like pipelines, pressure vessels, canisters, fuselages, and rockets are notable examples of the hollow cylindrical design. The integrity of these structures is crucial because damage to them will adversely affect the surrounding environment and result in loss of resources. In most hollow cylindrical structures/systems (like pipelines),

---

P. Shivashankar, J. Sohn, N. Wilson, G. W. Lee, & S. Salamone, Smart Structures Research Laboratory (SSRL), Maseeh Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, Austin, TX 78712, USA

corrosion is the chief cause of non-human-related failure. The effect of corrosion in metallic pipes is often seen in the form of wall thinning, pits, cracks, and crevices. To identify these defects, especially in pipelines, a few commercial NDE devices are used [1]. They efficiently locate large internal and external damages and are widely used for rapid pipe screening. However, these inspection procedures are typically time-consuming, as a point-by-point scan is required to gather global information about a structure. Also, the subjectivity associated with damage quantification and characterization further complicates the structural evaluation process. Hence, there is a need for new diagnostic tools and techniques that could locate and characterize the defects reliably without much supervision.

One attempt at this has been the helical guided ultrasonic waves (HGUW)-based tomographic methods [2–4]. Using HGUW, researchers have been able to tomographically locate, and in one case, quantify, the regions of thickness loss in metallic pipes. This method enables evaluation over a broader area without constant human supervision, using a few low-profile PZT discs. While the HGUW-based tomographic methods are effective in locating (and to some extent quantifying) prominent defects, they cannot be used to reliably characterize subtle defects like cracks. That is, these techniques cannot directly reveal the length, orientation, and depth of crack-like defects.

In the field of guided waves-based SHM, there have been relatively fewer attempts to characterize crack-like defects. A notable among these few attempts is the work of Davis and Cawley [5], wherein the authors proposed using backscattered reflections of the $T(0,1)$ mode to image a circumferential crack through synthetic focusing. From the image's defect amplitude plot, they established that the amplitude's full width at half maximum was equal to the crack length, provided the crack size was above $1.5\lambda_S$. Another recent attempt at this problem was from Shivashankar et al. [6, 7], wherein they proposed a HGUW-based method called the stepped-wavelength scattering analysis to determine the length of crack-like defects in hollow cylindrical structures. From numerical simulations, they established that as the wavelength-to-crack length ratio increased, from being $\ll 1$ to $\gtrapprox 1$, the interpretability of their results changed. Specifically, they claimed that the scattering directivity plots had a profile that was explainable through *ray-like* interactions when the wavelength was smaller than the crack length, and through *diffraction-dominated* interactions when the wavelength was approximately equal to or greater than the crack length. Further, they quantified this observation and created a criterion to determine the crack length.

This work discusses the extension of the stepped-wavelength scattering analysis for practical applications via circumferential measurements. The method in its original form requires measurements around the defect (i.e., circular measurements) to construct the scattering directivity plot, which is subsequently used to determine the defect length. While the mode of circular measurements was used to establish and validate the concept, it cannot be adopted for a general-purpose real-world setting. A practical alternative would be the mode of circumferential measurements, variations of which have already been used for testing real-world structures [8]. Accordingly, the procedure for using the circumferential mode to determine the orientation and length of crack-like defects is discussed in this paper.

The next section provides a brief overview of the stepped-wavelength scattering approach, followed by a description of the method for determining defect orientation.

The penultimate section presents a three-step procedure for implementing the HGUW scattering-based analysis to characterize crack-like defects in real-world structures. The final section concludes with a summary of the key discussions and remarks on future research directions.

STEPPED WAVELENGTH SCATTERING ANALYSIS

The stepped wavelength scattering analysis was proposed to determine the length of crack-like defects in hollow cylindrical structures based on the scattering of helical guided ultrasonic waves. The method was developed from the numerical results of an ABAQUS pipe model illustrated in Figure 1. The structure in the model is 40 cm long, with an outer radius of 15.24 cm and a wall thickness of 3 mm. The defect was a circumferential through-thickness notch, with lengths ranging from 12 mm to 15 mm. Actuation was applied at a point 20 cm axially from the midpoint of the notch, creating a direct incident path that bisected the defect perpendicularly. When the guided wave interacts with the defect, it scatters, and this scattering is characterized using the scattering directivity plot, which was constructed from responses obtained around the defect on a 5 cm radius circular array. Further details of the numerical model are available in previous studies [6, 7].

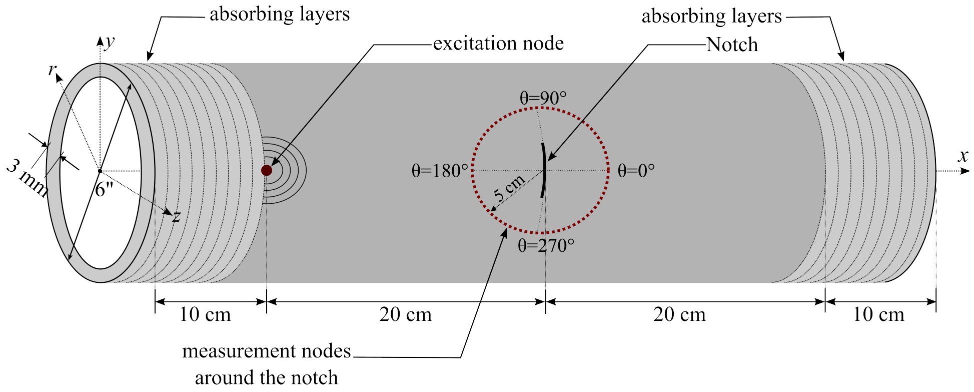

Figure 1. Schematic of the numerical model with a circumferential notch.

The defect length (l_c) is unknown and has to be determined. A set of excitation frequencies is selected to probe the defect through their scattering directivity plots. The frequencies are selected to correspond to an array of incremental wavelengths. In the studies, the excitation frequencies of 415, 340, 280, 240, 205, 175, 155, 135, 120, 105, 95, 85, and 80 kHz were selected as they result in A_0-like mode with respective approximate wavelengths of 6, 7, 8, 9, 10, 11, 12, 13, 14, 15.1, 16.1, 17.1, and 17.75 mm. The assumption of choosing a specific range is that the defect length lies within the range, i.e., $\lambda_{min} \leq l_c \leq \lambda_{max}$.

Scattering directivity plots were obtained at each of these wavelengths to observe the changes in their profile and subsequently identify the notch length. From the scattering directivity plots of the higher order arrivals $(h = (2, 3))$, it was found that when the wavelength is smaller than the notch length, i.e., $\frac{\lambda}{l_c} \ll 1$, the profile was well interpretable through a ray-like interaction. But when the wavelength was comparable to or greater than the notch length, i.e., $\frac{\lambda}{l_c} \gtrapprox 1$, the profile of the scattering directivity plot was dominated by diffraction. Based on this observation, the interaction was described as being *ray-like* for $\frac{\lambda}{l_c} \ll 1$, and being *diffraction-dominated* when $\frac{\lambda}{l_c} \gtrapprox 1$.

This visual observation was translated into a quantifiable metric with the first helical-order scattering directivity plots. Specifically, the areas of the damage index-based scattering directivity plots were evaluated and plotted against their respective wavelength. The plot has a minimum close to the notch length. In other words, the overall change to the wavefield due to the scattering is minimal when the wavelength is close to the notch length. A criterion was established per this observation and was validated with experimental results from a metallic pipe.

The previous work focused on determining the notch length from circular measurements. While a circular array was useful in establishing the concept, it cannot be adopted for a generalized implementation of this technique on a real-world structure. From a real-world applicability standpoint, the apt choice would be circumferential arrays. Variations of these have already been used in prior studies to map regions of wall thickness loss in pipes [2–4] and canisters [8]. In this work, the possibility of extending this technique with circumferential measurements is discussed. Before commencing that, the method to determine the crack-like defect orientation with the circular array is discussed. Accordingly, the following section presents the method to determine the defect orientation from the scattering directivity plots. With both procedures–methods to determine the length and orientation–established with the circular array, the final discussion would be that of implementing these two procedures with circumferential measurements.

ORIENTATION OF THE CRACK-LIKE DEFECT

Orientation, or the angle of the defect, can be identified from the direction of the lobes in the directivity plot obtained from ray-like interactions. That is, when a wave with a very small wavelength is used as the incident wave, the direction of the lobes in the directivity plot would be aligned according to the defect angle. This can be explained by using the following example.

A numerical model was created with the exact specifications listed in Figure 1, except that the notch is 15 mm and oriented at an angle of 45°to the *x*-axis. The excitation frequency of 415 kHz, corresponding to the A_0-mode wavelength of 6 mm, was used to probe the defect. The smaller value of the wavelength compared to the notch length implies that the interaction is *ray-like*. Figure 2a shows the resulting scattering directivity plot from the interaction of the first arrival.

The directivity plot exhibits two lobes; however, unlike those generated by a circumferential notch, the backward-scattered lobe is oriented toward the 90°direction. This scattering behavior, particularly the formation of the backward lobe, can be explained by *ray-like* interactions. As illustrated in Figure 2b, when the wavefront encounters the inclined notch, it gets reflected at an angle equal to the angle of incidence relative to the notch's normal. Thus, a prominent lobe is found at 90°. This reflection also produces a forward-scattered lobe at 0°, consistent with the symmetry of *ray-like* interactions. Together, the orientation of the lobes aligns with the orientation of the notch.

This scattering behavior can be leveraged to infer the orientation of a crack-like defect. For a defect with unknown orientation, an excitation at a relatively small wave-

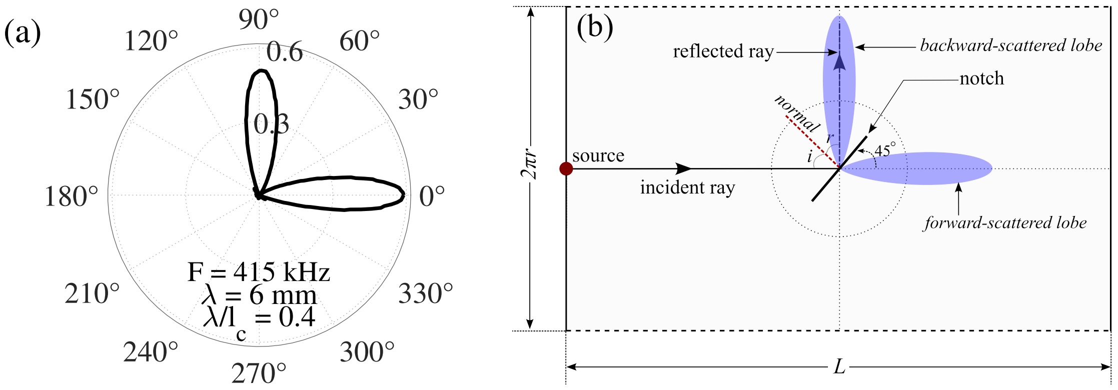

Figure 2. (a) Scattering directivity plot for a 15 mm crack oriented at an angle of 45°, and (b) the illustration explaining the formation of the scattering directivity plot based on *ray-like* interactions.

length can be used to ensure *ray-like* interactions. The resulting first-arrival scattering directivity plot can then be analyzed to estimate the defect's orientation. Specifically, the angular position of the lobes in the plot reveals the orientation of the defect that would give rise to the observed scattering pattern.

CIRCUMFERENTIAL MEASUREMENTS FOR REAL-WORLD STRUCTURES

Figure 3 shows the illustration of a circumferentially unwrapped pipe with sensors distributed in two circumferential arrays. As mentioned, variations of this configuration have been used earlier to map regions of wall thickness loss [2–4] and weld damage [9]. This configuration has also been tested on real-world canisters, confirming its applicability for practical implementation.

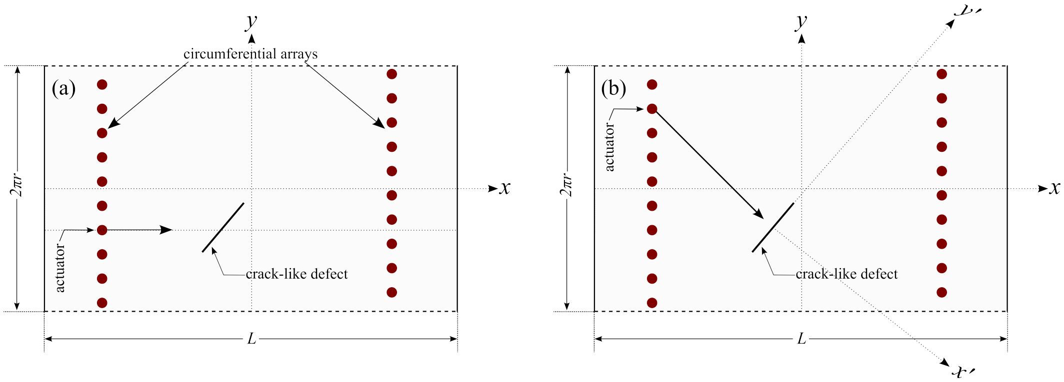

Figure 3. Illustration of a circumferentially-unwrapped hollow cylinder with two circumferential arrays showing the actuator selections (a) for estimating orientation and (b) defect length.

The steps to implement the stepped wavelength scattering analysis with the circumferential sensor arrays to determine a through-thickness crack's length and orientation are presented here. It is assumed that the defect's features and location are unknown.

(i) *Defect localization:* The first step involves localizing the crack-like defect. Using circumferentially distributed transducers, the defect can be located through helical guided ultrasonic wave (HGUW) tomography. Previous studies have demonstrated the feasibility of mapping defective regions using techniques such as RAPID [2,9] and ART [3,4]. Once the defect's location is identified, the subsequent steps focus on determining its orientation and length. It is worth noting that one study [10] has shown that, under favorable conditions–specifically, a sufficient number of transducers and a well-optimized reconstruction algorithm–the tomographic image may offer a rough outline of the defect geometry. However, such clarity is not typical.

(ii) *Defect Orientation:* With the defect location identified, the next step proceeds with obtaining the scattering directivity plot from the circumferential measurements for determining the orientation. The transducer closest to the axial line passing through the center of the defect will be designated as the actuator, while the rest will be used as sensors. Figure 3a depicts the choice of actuator for this step. An excitation frequency corresponding to a relatively small wavelength will be used to obtain the ray-like scattering directivity plot.

With the actuator and sensors designated, the next critical step is to extract the scattering directivity plot from the circumferential measurements. Recent work has demonstrated that circumferential responses indeed contain information about wave scattering around the defect [7], and that a general outline of the forward-scattered lobe can be directly constructed from these measurements. Although a method for reliably reconstructing the full circular-array-type directivity plot from circumferential data has not yet been developed, these findings suggest that a well-trained deep neural network (DNN) could learn to map circumferential measurements to their circular-array equivalents, thereby enabling the reconstruction of the complete scattering directivity plot. Developing such a DNN-based framework will be the focus of future investigations.

After the scattering directivity plot is obtained, the orientation of the defect can be inferred from the angular position of the scattered lobes, as discussed in the previous section. It is important to note that this step does not require the scattering directivity plot to match the exact amplitude profile of a circular-array-based plot. The version derived directly from the circumferential measurements is sufficient for orientation estimation. Furthermore, even if the actuator is not perfectly aligned with the axial line passing through the defect, the relative angle between the actuator path and the observed lobe directions can still be used to accurately determine the crack orientation.

(iii) *Defect length:* With the location and orientation of the defect known, its length can be determined using the stepped-wavelength scattering analysis. To reliably apply the established sizing criterion, it is important to select a transducer whose first arrival path is approximately perpendicular to the defect. With the defect orientation identified, the appropriate transducer satisfying this condition can be selected and designated as the actuator. Figure 3b illustrates this setup. In this case, the scattering directivity plot will be constructed with respect to a rotated coordinate system $(x' - y')$, aligned with the first arrival path and the defect orientation.

The steps outlined here provide a pathway for implementing the scattering-based analysis to track the growth of crack-like defects in real-world hollow cylindrical structures, such as canisters. A critical requirement for this implementation is the ability to reconstruct circular-array responses from circumferential measurements. Future studies will focus on developing reliable methods to achieve this reconstruction and on experimentally validating the proposed framework.

CONCLUSION

The steps for implementing the stepped-wavelength scattering analysis to characterize crack-like defects in real-world structures using transducers distributed in circumferential arrays were outlined. The overall approach involves three stages: (1) locating the defect, (2) determining its orientation from the angular positions of the lobes in the scattering directivity plots, and (3) estimating its length. For orientation estimation, the directivity plots constructed directly from circumferential measurements are expected to be sufficient. However, for applying the stepped-wavelength scattering analysis to estimate length, a directivity plot that closely matches the amplitude profile of a circular-array-based plot may be required. Achieving this would necessitate reconstructing circular-array responses from the circumferential measurements, potentially through a well-trained DNN model. Future work will focus on developing such a DNN framework and experimentally validating the full implementation strategy.

ACKNOWLEDGMENT

The authors gratefully acknowledge the United States Department of Energy, Nuclear Energy University Programs (Project 21-23997), and the Nuclear Regulatory Commission (Project 31310022M0005) for supporting this work.

REFERENCES

1. Livadiotis, S. 2022. “Pipeline health monitoring using helical guided ultrasonic waves,” *The University of Texas at Austin, USA*.
2. Dehghan-Niri, E. and S. Salamone. 2015. “A multi-helical ultrasonic imaging approach for the structural health monitoring of cylindrical structures,” *Structural health monitoring*, 14(1):73–85.
3. Livadiotis, S., A. Ebrahimkhanlou, and S. Salamone. 2019. “An algebraic reconstruction imaging approach for corrosion damage monitoring of pipelines,” *Smart Materials and Structures*, 28(5):055036.
4. Livadiotis, S., A. Ebrahimkhanlou, and S. Salamone. 2021. “Monitoring internal corrosion in steel pipelines: a two-step helical guided wave approach for localization and quantification,” *Structural health monitoring*, 20(5):2694–2707.
5. Davies, J. and P. Cawley. 2009. “The application of synthetic focusing for imaging crack-like defects in pipelines using guided waves,” *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 56(4):759–771.

6. Shivashankar, P., J. Sohn, S. Livadiotis, and S. Salamone. 2024. “Notch characterization in pipes from the scattering of helical-guided ultrasonic waves,” in *Health Monitoring of Structural and Biological Systems XVIII*, SPIE, vol. 12951, pp. 470–484.
7. Shivashankar, P., J. Sohn, and S. Salamone. 2025. “Tracking growth of crack-like defects in hollow cylindrical structures from the stepped-wavelength scattering of helical guided ultrasonic waves,” *Mechanical Systems and Signal Processing*, 236:112918.
8. LIVADIOTIS, S., G.-W. LEE, N. WILSON, and S. SALAMONE. 2023. “Structural Integrity Assessment of Nuclear Spent Fuel Canisters Using Guided Waves,” *STRUCTURAL HEALTH MONITORING 2023*.
9. Shivashankar, P., N. WILSON, G.-W. LEE, and S. SALAMONE. 2025. “Monitoring circumferential welds in canisters with helical ultrasonic guided waves,” *STRUCTURAL HEALTH MONITORING 2025*.
10. Hall, J. S., P. Fromme, and J. E. Michaels. 2014. “Guided wave damage characterization via minimum variance imaging with a distributed array of ultrasonic sensors,” *Journal of Nondestructive Evaluation*, 33:299–308.