

Damage Indicator Selection Under Measurement Uncertainty for Detecting Selective Leaching in Metal Pipes Using Ultrasonic Wave Pitch-Catch

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ABSTRACT

We develop a novel non-destructive evaluation (NDE) technique for detecting leaching damage using ultrasonic wave pitch-catch. This method combines guided wave propagation with advanced signal processing to detect leaching damage. In this method, ultrasonic guided waves travel from the actuator to sensor and interact with leaching damage on their path. The changes to the received wave signal due to leaching damage are quantified using three different damage indicators (DIs). Damage detection accuracy for these three DIs is investigated by conducting laboratory experiments on gray cast iron pipes. Leaching damage is induced in these pipes and piezoelectric transducers are attached to conduct ultrasonic wave pitch-catch and damage detection. For the three DIs, the most suitable DI that gives the highest sensitivity and specificity under measurement uncertainty is determined. Ultrasonic guided wave-based methods are found to be suitable for early detection of leaching damage detection.

INTRODUCTION

The underground metal pipes react with the surrounding environment during service life, which leads to corrosion damage and burst failure [1]. Selective leaching causes loss of strength and metallic properties without significant change in pipe dimensions, which is different from other corrosion mechanisms. We refer the reader to [2] for a detailed discussion on the process of selective leaching.

Many ultrasonic wave-based non-destructive evaluation (NDE) methods have been developed in the past for detection of pipeline damage. The most widely used method is the reflection wave method. We refer the reader to [3] [4] for a detailed discussion on the reflection wave-based method. Dispersion-based methods have also been employed to assess pipe wall health. This technique can provide a reference-

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free estimate of the pipe thickness [5]. A detailed review of ultrasonic NDE methods can be found in [3,6]. These NDE methods use a damage indicator to quantify the system health status. The damage indicator is a system response quantity that changes due to a change in health/damage state. In order to facilitate damage detection, the damage status is derived from the damage indicator value. Damage indicators are typically continuous variables with a range of possible values, but a damage status is a binary value depicting presence/absence of damage [7]. In this study, we focus on the damage indicators that compare the ultrasonic wave signal from the damaged and undamaged pipe, or *reference-based damage indicators*. Multiple reference-based damage indicators has been developed in previous study [8,9].

We develop a novel damage detection methodology framework for leaching damage detection that consists of the following: 1) ultrasonic pitch-catch test on undamaged (reference pipe) to build the probability distribution of measured response for undamaged pipe; 2) ultrasonic pitch-catch test on pipe with unknown damage status to build probability distribution for pipe with known damage; 3) quantification of the differences between the reference and test response under measurement noise.

METHODOLOGY

The proposed methodology involves conducting a pitch-catch test of a pipe. In this test, a guided ultrasonic wave originates from the actuator, travels along the pipeline wall, and is received by the sensor (see Figure 1). The signal received by the sensor contains information regarding material properties along the wave path. Different signal transforms are applied to the received signals (e.g. Fourier transform, continuous wavelet transform, Hilbert Huang transform) to extract important features. Damage indicators (DI) are constructed using the extracted features. The damage indicator is a system response quantity that changes due to a change in health/damage state. For example, the amplitude of the reflection wave is a damage indicator. A parameter quantifying the shape of the dispersion curve could also be the damage indicator. In order to facilitate damage detection, the damage status is derived based on the damage indicator. Typically, the damage indicator is a continuous variable and classifying a pipe as *damaged* or *undamaged* requires knowing the value of DI for the undamaged (reference) pipe. If the DI for a tested pipe is significantly different from the reference value, the pipe is deemed to be damaged. The damage detection thus involves (a) quantifying the difference between the DI from the reference (undamaged) and test system (denoted by ΔDI), (b) setting a ΔDI threshold (denoted as T) to identify system damage denoted as T , and (c) calculating the damage status (DS) as:

$$\begin{aligned} DS &= 1 \text{ if } \Delta DI > T \\ DS &= 0 \text{ if } \Delta DI \leq T \end{aligned} \quad (1)$$

The damage threshold is a hyperparameter used in damage detection process. If the damage status is 1 then the system is classified as *damaged*, and damage status value is 0 means the system is determined to be healthy. This study employs multiple damage indicators, which are discussed below.

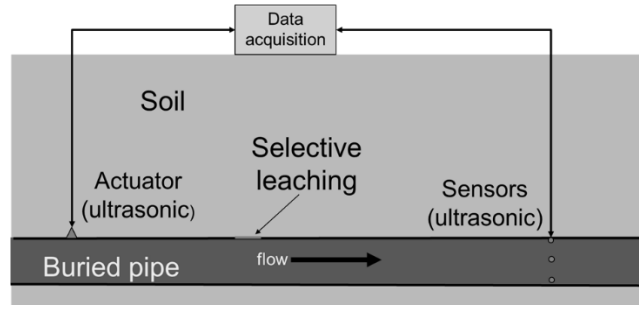


Figure 1. Guided wave propagation for detecting selective leaching in metal pipes

Damage indicators, ΔDI , and damage indicators

Energy Magnitude Indicator (EMI)

This damage indicator utilizes the Fourier transform to construct a damage indicator based on the energy content of the propagating wave. To calculate ΔDI , Fourier decomposition is performed on the reference and test signal. The discrete Fourier transform (DFT) result is denoted as $X[k]_r$ & $X[k]_t$ for reference signal and test signal, respectively, where k denotes the frequency. The sum of the magnitude of $X[k]_r$ & $X[k]_t$, denoted as $\sum |X[k]_r|$ & $\sum |X[k]_t|$, is used as the damage indicator. The damage indicator of the differences between $\sum |X[k]_r|$ & $\sum |X[k]_t|$ is taken as ΔDI :

$$\Delta DI = \frac{\sum_{k=1}^n (|X[k]_r| - |X[k]_t|)}{\sum_{k=1}^n (|X[k]_r|)}, \quad (2)$$

where n is the number of frequencies below the cut-off frequency, and the cut-off frequency can be chosen based on the input (actuation) signal frequency range. ΔDI is then used in Equation (1) to determine the damage status.

Image difference coefficient (IDC)

This damage indicator is based on continuous wavelet transform (CWT), which decomposes a signal using wavelet functions as the basis and provides a time-frequency signal representation [9]. The result of this transformation is a matrix (*CWT matrix*), where each element corresponds to a transformed value that reflects both the scaling and the shifting of the wavelet relative to the original signal. The damage indicator is set to be the CWT matrix itself, and the ΔDI is given by comparing the similarity of the columns in the CWT matrix. The mathematical form of the IDC is given as follows:

$$\Delta DI = 1 - \frac{1}{N} \sum_{i=1}^N \max_{j=1:N} \rho(R_i T_j), \quad (3)$$

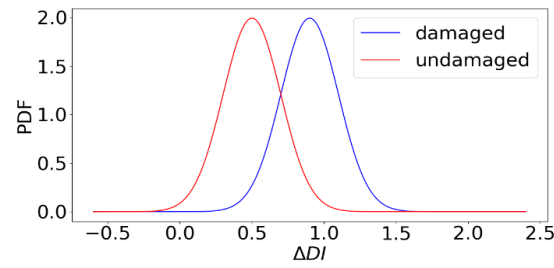


Figure 2. Overlap of the ΔDI distribution

where R_i means the i^{th} column of the reference CWT matrix and T_j means the j^{th} column of the test CWT matrix. ΔDI is then used in Equation (1) to determine the damage indicator.

Signal correlation (SC)

In this case, the shape of the received signal is taken as the damage indicator. The correlation coefficient can measure the wave shape change: if two waves have the same shape and only amplitude is different, then the correlation coefficient is 1. The ΔDI of this method is as follows:

$$\Delta DI = \text{abs} \left(\frac{\text{corr}(R, R)}{\rho_R \rho_R} - \frac{\text{corr}(R, T)}{\rho_R \rho_T} \right), \quad (4)$$

where ρ is variance and corr is correlation coefficient. ΔDI is then used in Equation (1) to determine the damage indicator.

Analysis of measurement uncertainty

For all damage indicators, the method assumes that for a given (fixed) damage severity, the DI value does not change. However, due to measurement noise, the DI value changes and can be represented by a probability distribution. The ΔDI is also a distribution (see Figure 2). Also, due to the measurement uncertainty, the system response might be different, even if the test pipe is not damaged, and the ΔDI value of undamaged pipe could also be represented using a probability distribution. The probability distributions of ΔDI for damaged and undamaged pipes may overlap, leading to ambiguity in the detection results. This overlap can significantly affect damage detection accuracy. Therefore, the damage indicator that has lowest damage overlap area shall be chosen as the best DI. We use data from controlled leaching and ultrasonic pitch-catch testing experiments to arrive at the best DI.

EXPERIMENTS

To illustrate the damage detection and DI selection, we perform experiments on three gray cast iron pipe specimens.

TABLE I. CHEMICAL CONTENT IN THE CORROSIVE SOLUTION.

Chemical name	NaCl	H ₂ SO ₄	HCl
concentration	0.1M	0.05M	0.001M

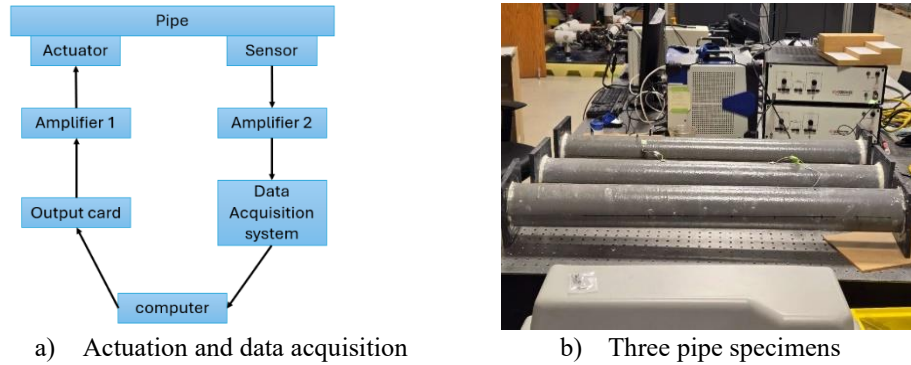


Figure 3. The experiment system setup

Corroded pipe specimen preparation.

All pipe specimens have a 3.5-inch outer diameter and a 3-inch inner diameter, A 0.25-inch-thick inner protection layer, 3 feet length. The outer surface of the pipe is sandblasted to remove the original corrosion protection layer, and the specimens were coated with epoxy to provide a uniform, well-controlled layer of protection. A small region near the center of the specimens was left uncoated for two out of three specimens. The uncoated area for the two specimens is 1 in² and 3 in², respectively. The entire outer surface was coated for the third specimen. Two uncoated pipes are then immersed in leaching-inducing acidic solution. The chemical content of the solution is summarized in Table 1. Pipe specimens were removed from the corrosive solution after 19 weeks. Selective leaching damage is induced in the unpainted region. During the corrosion test process, the pH of the solution is monitored. Consumption of H⁺ ions is used to estimate the volume of leached material. It can be estimated that the corroded region volume for the two pipes is approximately 0.12 cm³ and 0.36 cm³ respectively.

Ultrasonic pitch-catch test experiment setup

All three specimens are subjected to the ultrasonic pitch-catch test. The distance between the sensor and the actuator is 1 foot. The experiment setup and the test system are shown in Figure 3. The excitation signal is a Hanning-modulated pulse signal with 128Khz mean frequency and 10 cycles.

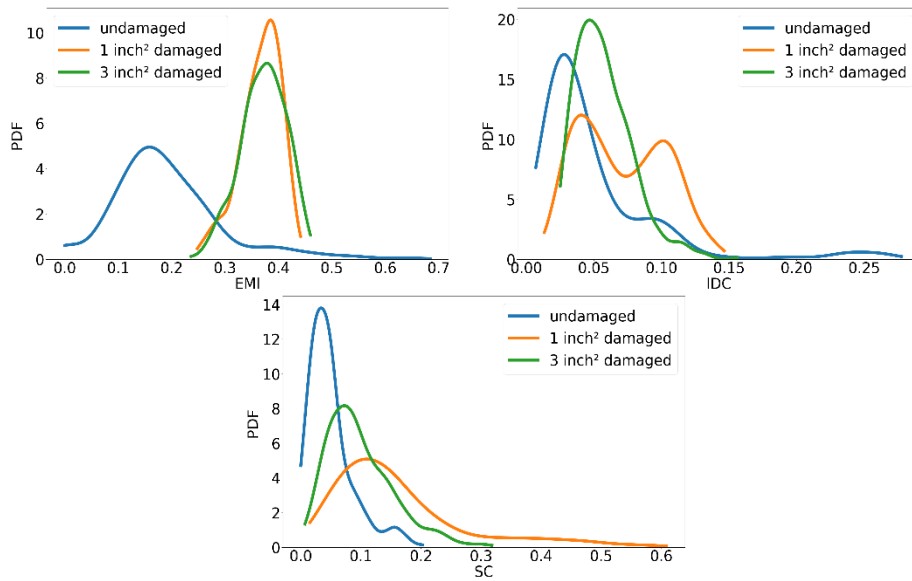


Figure 4. Probability distributions of ΔDI for different damage areas

RESULTS

The pitch-catch experiments are repeated 25 times on each pipe sample. With the undamaged pipe response as reference signal and damaged pipe response as test signal, probability distributions of ΔDI for undamaged and damaged pipe samples are generated (see Figure 4). For all three damage indicators, some overlap can be observed in the ΔDI probability distribution. The overlap area of IDC and SC is 0.61 and 0.47, respectively. EMI shows the best performance with an overlap area of 0.16.

CONCLUSION

In this study, we developed an ultrasonic wave pitch-catch-based method to detect leaching damage in gray cast iron pipes. We examined the feasibility of multiple damage indicators and assessed their performance in terms of accuracy using the experimental data taken from in-service pipe samples. We also developed a method to determine the best damage indicator under measurement uncertainty using data from laboratory experiments.

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