Characterization of pipeline defect in guided-waves based inspection through matching pursuit with the optimized dictionary

Peter W. Tse *, Xiaojuan Wang

The Smart Engineering Asset Management Laboratory (SEAM) and The Croucher Optical Non-destructive Testing and Quality Inspection Laboratory (CNDT), Department of Systems Engineering and Engineering Management, City University of Hong Kong, Tat Chee Avenue, Hong Kong, China

Abstract

An optimized dictionary of matching pursuit (MP) is designed and combined with the ultrasonic guided wave for characterizing pipeline defect, which consequently achieves good performance in estimating the axial length of a defect. In the research field of guided wave based pipeline defect inspection, quantitative characterization on the detected defect remains as an unsolved research task and is seldom reported in the related publications. This paper reports a new method of MP equipped with an optimized dictionary through analyzing the interference between the reflection components embedded in a defect reflection signal in order to enable efficient extraction of defect information. The proposed method not only enhances signal-to-noise ratio of reflection signal, but also characterizes the axial length of pipeline defect directly and accurately. The method has been verified by simulated data, artificial defects in real pipes as well as real corrosion in a servicing pipe.

1. Introduction

The advanced technique of ultrasonic guided waves [1] is now in routine use of nondestructive testing (NDT) fields. Many progresses and advancements have been made for the application of guided waves in inspecting pipeline. However, the quantitative evaluation of defect sizes or severity is always a challenging task in NDT after a pipe defect has been found because of the complexities included in the reflection signal [2]. The scale of difficulty magnifies in real practices as the reflected waves are subjected to the contamination from a diversity of noise sources. Such sources could be randomly generated environmental noise, unexpected modes from mode conversion and coherent noises introduced by the irregularity of defect as well as the reverberation of waves. The insufficient defect information prevents an accurate indication of damage severity without applying additional testing or direct measurement. To carry out maintenance remedy on defective pipelines properly and efficiently, the ability of characterizing pipeline defect is very important, particularly for the cases in which the locations of defect are difficult to be accessed, such as buried pipelines or pipelines inside walls.

Most of the methods currently available for long-range inspection of pipeline defect are only capable of providing a qualitative or semi-quantitative assessment of defects. Few research works have been conducted on the possibility of using guided waves for characterizing pipeline defects in a quantitative manner. Mu et al. [3] determined the defect’s circumferential extent by comparing the theoretical reflection profiles to the experimental results obtained through performing circumferential focusing scan. Li [4] developed an algorithm based on two-dimensional blind deconvolution to evaluate the circumferential size of the defects using multiple reflection waveforms acquired by a multiplexed circumferential transducer array. Satyarnarayan et al. [5] investigated circumferential higher order guided wave modes to estimate the size of defect in pipe support region. These methods are supposed to optimize the specific parameters of excited guided waves or construct sophisticated configuration of transduction system so as to achieve well-defined or controlled waveform of reflection for defect characterization. They usually require a great deal of experimental care and tremendous time to increase the precision and reliability of instrumentation and the repeatability of measurements. Other methods for defect characterization tried to use simpler and less specific transducers, thus decreasing the complexity of instrumentation and installation for practical applications. A good example is presented by Demma et al. [6] works. They investigated the effect of defect parameters on reflection for possible interpretation of defect size information. Recent advancements include the utilization of imaging and tomography techniques for defect characterization. For example, Hayashi and Murase [7] developed a defect image technique through reconstructing the spatial waveforms that had been separated into several single-mode signals. However, the post processing of reflected waves for defect characterization contains more difficulties.
due to the complicated interaction process of guided waves with different defects. Advanced signal processing techniques are always needed to purify the reflection signal so that higher chance of success in defect characterization can be realized. Although the above techniques have proven to be successful in various degrees, they are in generally time and cost consumption but the results contains uncertainty in the accuracy of characterizing defects. Moreover, they still cannot provide the ability of directly characterizing pipeline defects by only analyzing the defect reflection signal.

2. Defect characterization with reflection components

It is important to understand reflection procedure for quantitative and accurate characterization of defect. It has been found by some researchers such as Demma et al. [8,9] that the reflection of guided waves from a defect is primarily resulted from the interference between the two reflection components generated at the edges of the defect. We further revealed in our earlier research work [10] that the complexity of the reflection signal was essentially a result of the different features represented by the front-edge and back-edge reflection components. Two edge reflection signals exhibit similar wave patterns in terms of the number of cycle, frequency, and modulation but have different amplitude and duration of phase shift. The reflection coefficient of total resulting defect reflection signal thus exhibits a periodic variation with the change of axial length of defect. That is, the total reflections are being constructive in some defect cases while being destructive in some other defects cases, due to interference between the reflections from two edges of defect. It is noted that in all of the above studies, the researchers mainly used artificial defects to develop simplified models, such as notched or circular hole, to approximate the case of real defects or corrosion in pipeline. The real pipeline defect is far more complex and irregular at its three dimensional profiles. Demma [11] indicated that maxima and minima of reflectivity resulted from the interference of two reflection components could occur on real defects that would not have a sharp and rectangular profile in practical inspection. Ma and Cawley [12] further employed a part-thickness taper elliptical defect model as a closer match to real corrosion shape for investigating the effect of different defect parameters on the reflection. Their research showed that reflection ratio spectrum from such a complex defect still exhibited periodic pattern due to the interference between reflections from the two edges of defect. That is, all of these researches suggest that reflection signal captured even from a complex defect mainly consists of two reflection components from the front and back edges of defect, and the respective contribution of different parameters of defect to overall defect reflection can be affected by the features of these components. The identification of these two primary components embedded in defect reflection signal is therefore greatly useful to characterize the concerned defect.

Considering the distance between two reflection positions, which are at the front and back defect edges, is closely related to the axial length of defect. Hence, the identified reflection components could thus help to determine the value of axial length. Moreover, they can enable the evaluation of more defect parameters because each identified edge signal embeds geometric information such as circumferential extent and radial depth of the corresponding edge of the defect. Therefore, the decomposition of reflection signal together with the identification of axial length of defect is a very important step for comprehensive defect characterization. The axial length obtained through the use of primary reflection components refers to the characteristic value of real axial length since the generation of these components is strongly affected by the combined features of the defect edge's parameters. In this research, a method in the frame of matching pursuit (MP) decomposition technique with an optimized dictionary was developed to resolve the primary reflection components from defect reflection signal so that the quantitative characterization of defect length can be realized. MP is a time–frequency signal analysis technique for decomposing the waveform into a linear combination of basis functions as defined in a dictionary. During the stage of developing our method, the prior knowledge about the relationship between the edge reflection components and their respective features was adopted as prior information to establish the required dictionary for MP decomposition procedure. This method not only provides an ability of efficient noise immunity for the complex guided wave reflection signal, but also enables the characterization of defect length directly from the defect's reflection signal. The rest of the paper starts with a detailed description of the rationale of the proposed method in Section 3, especially the construction of the dictionary optimized for the concerned application. In Section 4, the proposed method is applied to the simulated signals to illustrate its ability. The performance of our method is further investigated and presented in Section 5, in which the experiments conducted on arbitrary defects and real corrosion in the tested pipe samples as well as the experimental results are stated in details. Finally, the special observations, the conclusion and the potential of research outcomes are summarized in Section 6.

3. Matching pursuit with optimized dictionary for characterizing axial length of defect

As explained in Section 2, both reflection components exhibit nearly the same patterns in terms of the frequency, cycle number, and modulation, but are different in phase, regardless of dispersion effect as it can be controlled with proper arrangement of transduction system. Once they have been decomposed and correctly recovered to their original temporal waveforms, then the characterized axial length of defect will be easily determined based on the wave group velocity and the time shifts of two primary reflection signals. It has been indicated in Section 2 that these reflection components appear in the collected defect reflection signal with an interference form. The interference will not only result in the complexity of waveform, but also cause the lost of interested information relevant to defect characteristics. Most of the conventional time–frequency signal processing methods are inadequate in identifying edge reflection components, especially under the cases in which substantial environmental noises and coherent noises are embedded in the reflection signal. Here, we proposed the method of optimized matching pursuit for decomposing the reflection signal so that the original reflections caused by the front-edge and the back-edge of the defect can be recovered for estimating its axial length.

3.1. Matching pursuit decomposition

Matching pursuit (MP) decomposition is a highly adaptive time–frequency signal processing technique introduced by Mallat and Zhang [13]. A similar algorithm was developed independently by Qian and Chen [14]. It can decompose any given signal into a linear expansion of components that belong to a redundant dictionary of waveforms. The dictionary is a collection of parameterized waveform atom, which is presented by amplitude, phase, frequency, or other vital parameters. The components are selected from the dictionary to approximate the signal structures so that any interested information embedded in the signal can be reconstructed. That is, MP can provide a representation or interpretation of signal structure through decomposition process.
To explain MP decomposition, assuming \([y_1, y_2, \ldots, y_l]\) is the noisy observation of a target function \(f\) at points \([x_1, x_2, \ldots, x_l]\). Given an over-complete dictionary \(D = \{g_1, g_2, \ldots, g_N\}\), which is a redundant collection of unit vectors in a Hilbert space \(H\), the function \(f\) can be decomposed into a linear expansion of \(N\) atoms selected from \(D\) and a residual term \(R_N(t)\), as follows:

\[
f(t) = \sum_{n=1}^{N} a_n g_n + R_N(t), \quad ||g_n|| = 1
\]  

(1)

\[
f_N = \sum_{n=1}^{N} a_n g_n
\]  

(2)

where \(\{g_1, g_2, \ldots, g_N\} \subset D\) is the basis of this expansion, and \(\{x_1, x_2, \ldots, x_N\} \subset R_N\) is the set of corresponding coefficients of the expansion. \(f_N\) presents an approximation of \(f\) through selecting \(N\) proper basis atoms from the dictionary. The algorithm is to select the basis \(\{g\}\) and the corresponding coefficient \(\{a\}\) so that they can iteratively minimize the second-order norm of the residual component for optimal approximation:

\[
||R_N||^2 = ||f - f_N||^2 = \sum_{i=1}^{l} (y_i - f_N(x_i))^2 = \min
\]  

(3)

In the first step of matching pursuit, the waveform atom \(g_0\) that best matches the given signal \(f\) is chosen through evaluating the similarity by inner product. The attractive theoretical properties of MP algorithm guarantee the rigorous proofs of exact reconstruction in many applications [15]. Assuming the signal has been decomposed to \(M = 1 \geq 0\) atoms, the further an \(M\)-atom decomposition in the consecutive steps is performed as follows [16]:

1. Compute \(|\langle R_{M-1}, g \rangle|\) for all \(g \in D\);
2. Select an atom that best matches the residual \(R_{M-1}\) from the dictionary:
   \[
   |\langle R_{M-1}, g \rangle| \geq \rho \sup_{g \in D} |\langle R_{M-1}, g \rangle|,
   \]
   where \(0 < \rho \leq 1\) is some number independent of \(M\).
3. Compute the new residual as
   \[
   R_M(t) = R_{M-1}(t) - \langle R_{M-1}, g \rangle g_M(t).
   \]

The signal based on \(M\)-atoms after \(M-1\) decomposition interactions can be then represented with a finite expansion as

\[
f(t) = \sum_{n=1}^{M} \langle R_n, g_n \rangle g_n(t) + R_M(t)
\]  

(4)

Matching pursuit can maintain energy conservation during decomposition, which guarantees its convergence [14]. For a complete dictionary, matching pursuit procedure converges to \(f\)

\[
f(t) = \sum_{n=1}^{\infty} \langle R_n, g_n \rangle g_n(t)
\]  

(5)

3.2. The optimized dictionary based on two interfering reflection components (IRC-dictionary)

As indicated by Mallet and Zhang [13], MP decomposition provides extremely flexible signal representation since the choice of dictionaries is not limited. The time–frequency atoms in a dictionary are dilations, translations, and modulation of an elementary function. The convergence \(||R(t)||^2\) of residual is independent of the type of elementary function used for matching pursuit in principle. That is, we could use any function to match the given signal so that optimal approximation for a specific application could be achieved.

The classic MP dictionary usually uses Gabor functions and consists of waveforms described by different parameters, for example, frequency, time span, amplitude, and phase [17,18]. Such dictionary works adequately for enhancing the resolution in conventional ultrasonic inspections but is inappropriate in the application of characterizing complex defect reflection signals. Our research aim is to establish a new MP dictionary optimized through correlating the underlying physical mechanisms of the concerned application to incorporate the features of reflection signal. As discussed in Section 2, the reflection signal from a pipeline defect primarily includes the reflection components generated at the two edges of defect. The waveform of each signal reflected from any edge of the defect can be described as a time-delayed and amplitude-scaled replica of the toneburst signal used in excitation. The excitation signal \(S(t)\) used in our research was a Hamming windowed toneburst consisting of five cycles, as shown below

\[
S(t) = \sin(2\pi ft)(0.08 + 0.46(1 - \cos(2\pi ft/5)))
\]  

(6)

Considering the interference structure of primary edge reflection components in reflection signal, the dictionary with the atoms representing the two interfering reflection components is designed and termed as the IRC-dictionary here. That is, the prior knowledge about the relationship between the two edge reflection components and their respective features is adopted to construct the atom of dictionary for MP decomposition procedure. The two edge reflection waveforms appears in the each defined atom \(g\) with an interfere structure.

\[
g(t) = \sum_{i=1}^{2} \text{sgn}(\cdot) A_i S_i(t + \theta_i), \quad ||g||^2 = \int |g(t)|^2 dt = 1,
\]  

(7)

where \(A\) and \(\theta\) are amplitude and phase index respectively. As the current authors indicated in their previous work [9], the first component that corresponds to front edge reflection always keeps constant while the second component that corresponds to back edge reflection changes at amplitude and phase with the change of axial length of defect. Some examples of the atoms in IRC-dictionary are presented in Fig. 1. The atoms in a row illustrate that the time shift between two components embedded in each atom varies gradually, and the atoms in a column illustrate the variation at amplitude of the components in atoms.

Such function provides a relationship to correlate the atom to any defect reflection signal, which can also be applied to the results of signal decomposition procedure for characterization purposes. Hence, the matching pursuit decomposition with IRC-dictionary not only provides improved signal-to-noise ratio (SNR), but also localizes and characterizes the two edge reflection components.

![Fig. 1. Examples of the atoms in IRC-dictionary.](image-url)
components directly from the decomposition parameters. The main question is how to select the dictionary atom with the appropriate parameters \((A_1, \theta_1, A_2, \theta_2)\) to match the collected defect reflection signal.

### 3.3. IRC-dictionary based MP for defect characterization

In the process of characterizing axial length of pipeline defect, it firstly constructs defect reflection signal and then determines the corresponding physical edge reflection components. Since reflections occur at both the front edge and the back edge of the defect, the resultant reflection components embed in the overall defect reflection signal are in pairs. By using the IRC-dictionary to match the overall reflection signal, primary edge reflection components can be efficiently reconstructed, thereby providing a significant advantage in increasing signal-to-noise ratio. The reconstructed result mainly includes the information that can be used for accurate defect characterization. Reconstruction procedure of primary reflection components further enables the determination of parameters of components involved in reconstruction. Because the use of IRC-dictionary inherently provides the correlation of reconstructed signal with the physical process of reflections at the two edges of defect, the concerned primary reflection components can be finally identified through a limited interactive process. The illustration of proposed method is presented in Fig. 2.

The procedure of evaluating axial length of defect is summarized as follows:

**Step 1:** generate an optimized IRC-dictionary based on prior information of the excitation signal, \(S(t)\), used in a specific inspection;

**Step 2:** carry out matching pursuit (MP) algorithm by using the IRC-dictionary on the collected defect reflection signal, \(y(t)\), until defined stopping criterion has been met;

**Step 3:** reconstruct the defect reflection signal, \(f(t)\), using the decomposed atoms obtained in Step 2;

**Step 4:** enable the determination of the parameter features (time shift, amplitude) of the embedded components in the reconstructed defect reflection signal, that correspond to the front-edge reflection signal \(S_1(t)\) and the back-edge reflection signal \(S_2(t)\), with the information of atoms in the IRC-dictionary:

**Step 5:** obtain the front-edge and back-edge reflection signals accordingly; and

**Step 6:** evaluate the axial length of defect by using the knowledge of the obtained edge reflection signals.

### 4. Numerical investigation

In this section, the performance of the proposed MP based method is investigated through applying it to a simulated reflection data. As mentioned in previous sections, environmental noise and coherent noise must be considered for accurate defect characterization in practical cases. To examine the tolerance of the proposed method in adverse environment, artificial noises were added into the simulated reflection signals. In the first two cases, a simulated reflection signal \(f(t)\), which has comprised the two time-shifted signal components assumed to have originated from two edges of the pipe defect, is used and defined as in the following equation:

\[
f(t) = S_1(t; a = 1, \theta = 5.07E-4) + S_2(t; a = 0.8, \theta = 5.148E-4)
\]

where \(S_1\) and \(S_2\) refer to the simulated front-edge reflection signal and back-edge reflection signal, respectively. \(a\) is the amplitude (volt) and \(\theta\) is the phase (second) of the reflection component. The resulting time shift of two components is thus \(7.8E-6s\), which ensures that their temporal waveforms are overlapped for method validation. Accurate determination of this parameter can lead to an efficient evaluation of the distance between the positions where simulated reflections happen, as indicated in Section 3. Assuming \(f(t)\) has been corrupted by a random white noise \(e(t)\), the noisy signal \(\hat{f}(t)\) can be written as

\[
\hat{f}(t) = f(t) + e(t)
\]

where the signal-to-noise ratio (SNR) is defined as

\[
SNR = 10 \log_{10} \left\{ \frac{\sum |f(t_i)|^2}{\sum |e(t_i)|^2} \right\} (dB)
\]

Relevant parameters of the signal under analysis in cases 1 and 2 are tabulated in Table 1.

The temporal signals of the first and second reflection components generated by the front edge and back edge respectively are shown in Fig. 3(a). The overlapped waveform after the aggregation of the two reflection components is shown in Fig. 3(b). Fig. 4 presents the noisy signals under various SNRs: 15 dB for case 1 in Fig. 4(a) and 5 dB for case 2 in Fig. 4(b). The results of reconstruction using MP equipped with IRC-dictionary for the two cases are exhibited in Fig. 5(a) and (b). The two estimated reflection components of the front and back edges after the decomposed process for cases 1 and 2 are shown in Fig. 6(a) and (b), respectively. Fig. 7(a) and (b) presents the reconstructed defect reflection signals as well as the residual signals from the given signals as shown in Fig. 4 for case 1 with the SNR at 15 dB and case 2 with the SNR at 5 dB, respectively. The residual signal can help to understand the noise level and the presence of other

### Table 1

<table>
<thead>
<tr>
<th>Parameters of simulated signals in case 1 and case 2.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse number</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>Case 1</td>
</tr>
<tr>
<td>Case 2</td>
</tr>
</tbody>
</table>

---

![Fig. 2. The schematic diagram of interference matching pursuit for decomposition of edge reflections.](image-url)
The prescribed time shift between two components and the estimation counterpart are identified and tabulated in Table 2. The relative errors indicate that the proposed method can provide excellent estimations of the two reflection components together with their time shifts, even under small SNR. The results also exhibit that the proposed method can provide good immunity to noise embedded in the reflected guided wave signals.

Another three cases were simulated to examine the performance of the proposed method when reverberation effect was considered. Different situations that may occur in pipeline inspection practice were considered in these three cases, which involved the normal reverberation, the reverberation with small time-shift and the reverberation with small reflection amplitude. Two additional components \(S_3, S_4\) were added into
the simulated reflection signal consisting of two edge reflection components \( (S_1, S_2) \) as the reverberation signal, which had lower amplitudes than the simulated main reflection components. Only the first two primary components were to be reconstructed as the simulated reflection signal for the purpose of axial characterization. Actually, in practice, the small rear reflection components in reverberation are prone to attenuation during propagation, thus being neglected in the collected data. Reflection signals in the four cases are expressed as below and the relevant parameters are tabulated in Table 3.

\[
f(t) = S_1(t; a = 1, \theta = 5.07E\text{E}^{-4}) + S_2(t; a = 0.6, \theta = 5.134E\text{E}^{-4}) \\
+S_3(t; a = 0.2, \theta = 5.198E\text{E}^{-4}) + S_4(t; a = 0.05, \theta = 5.262E\text{E}^{-4})
\]

(11)

\[
f(t) = S_1(t; a = 1, \theta = 5.07E\text{E}^{-4}) + S_2(t; a = 0.3, \theta = 5.17E\text{E}^{-4}) \\
+S_3(t; a = 0.1, \theta = 5.27E\text{E}^{-4}) + S_4(t; a = 0.01, \theta = 5.37E\text{E}^{-4})
\]

(13)

The temporal signals of four simulated components, which include the reflection signals from the front edge (the first component), the back edge (the second component) and the two signals from the reverberation (the third and fourth components) are shown in Fig. 8(a), (b), (c) for cases 3, 4 and 5 respectively. Correspondingly, the finally overlapped waveforms in the above three cases are presented in Fig. 9(a)–(c). The noise of 5 dB was introduced into the signals, as shown in Fig. 10(a)–(c) for the three cases. By using the proposed methods, signal components that correspond to simulated front-edge and back-edge reflection signals were obtained, which are presented in Fig. 11(a)–(c). Fig. 12(a)–(c) presents the reconstructed defect reflection signals as well as the residual signals from the given signals in Fig. 10 in three cases. The results are summarized in Table 4. The relative
Fig. 8. The four components of simulated signals with different amplitudes and time shifts in (a) case 3; (b) case 4; and (c) case 5.

Fig. 9. The overlapped signals after the aggregation of the four components in (a) case 3; (b) case 4; and (c) case 5.

Fig. 10. The simulated signals with 5 dB-SNR noise introduced in (a) case 3; (b) case 4; and (c) case 5.
errors are arranged from 0.78% to 8.69%, which indicate that good estimations of time shift between two components have been achieved.

5. Experimental results

In order to validate the performance of proposed method in evaluating the axial length of practical defect, experiments were conducted on a number of pipe samples with artificially introduced notches. To simplify the mechanical processing of defects and clarify the principle of proposed method, only circumferential pipe defects were considered herein. The experimental setup and instruments used are depicted schematically in Fig. 13. All of the examined steel pipe samples have an external diameter of 34 mm, a wall thickness of 4 mm and a length of 2030 mm. The artificial notches, which were simulated as defects, have radial depths that keep constant at 21.25% of the pipe wall thickness and the circumferential extents covering 100% ($360\degree$) of the pipe circumference. Over the course of experiments, the values of axial length were gradually increased using a milling machine to manufacture the notches at varying axial lengths. The transduction system of experiments was properly designed and the mode of excitation signal was optimally selected so that only the expected non-dispersive longitudinal mode $L_{(0,2)}$ was excited whilst the undesired flexural modes were suppressed.

The reflection signals from defects with axial length of 6 mm and 16 mm are used in the following discussion to illustrate the performance of proposed method. These two reflection signals are shown in Fig. 14(a) and (b). Clearly, by observing the overlapped reflection signals in Fig. 14, the reflection signal generated by the 6 mm-length defect represents the superposition effect in
amplitude whereas the other reflection signal from the larger 16 mm-length defect represents the cancellation effect.

Results of the analysis conducted by using the proposed method are presented in Fig. 15(a) and (b) for the defects with axial lengths of 6 mm and 16 mm, respectively. They show the two identified front-edge and back-edge reflection components decomposed from the original reflection for two defect cases.

Table 5
Evaluation results of defect sizes in cases of 6 mm- and 16 mm-defect.

<table>
<thead>
<tr>
<th>Actual defect size (mm)</th>
<th>Evaluated defect size (mm)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 6</td>
<td>6</td>
<td>5.89</td>
</tr>
<tr>
<td>Case 7</td>
<td>16</td>
<td>16.43</td>
</tr>
</tbody>
</table>
The testing of two defects with different axial lengths. The relative back-edge signals, respectively. Table 5 shows the results of using the cross-correlation function as defined in the following equation:

\[ T_s = \max \left( \frac{1}{T} \int_0^T S_1(t)S_2(t+\tau)dt \right) \]

where \( T \) is the observation time, and \( S_1 \) and \( S_2 \) are the front- and back-edge signals, respectively. Table 5 shows the results of testing of two defects with different axial lengths. The relative errors are ranged from 1.83% to 2.69%. It has proven that the proposed method can provide good evaluation performance even when the axial length of the defect is very small.

Since the proposed method has performed well in de-noising, it can be applied in a very noisy environment. In order to further verify the effectiveness of the proposed method, particularly when complex pipeline corrosion exists, a test was continued by using the same transduction system as shown in Fig. 13. This test was conducted on a real corroded gas pipe. The pipe was provided by a natural gas supplier in Hong Kong. It has a naturally developed corrosion, which is a commonly occurring defect in Hong Kong due to its humid and saline environment. The pictures of the tested pipe and its corrosion are shown in Fig. 17. The tested gas pipe has an external diameter of 88.6 mm and a wall thickness of 5 mm. The corrosion is distributed along the entire circumference of the pipe and has a non-uniform axial length of 59 ± 5 mm. Detailed information of this corrosion is given in Table 6 and the profile of axial length of the corrosion along the circumference is also plotted in Fig. 18. Two cases with their central frequencies of excitation set at 160 kHz and 110 kHz were considered. The edge reflection components in the 110 kHz case were more overlapped than that in the 160 kHz case. The original waveforms of the reflection signals generated from the real corrosion with excitation signal set at 160 kHz and 110 kHz are shown in Fig. 19(a) and (b) respectively. The decomposed front- and back-edge signals are shown in Fig. 20(a) and (b) for the central frequencies of excitation set at 160 kHz and 110 kHz respectively. The reconstructed reflection signals and the residual signals decomposed from the original signals are presented in Fig. 21(a) and (b) respectively. The results are summarized in Table 7. They indicate that good evaluation of the axial length of the corrosion has been achieved with the maximum relative error of 6.34%.

### Table 6

The description of the real corrosion tested in the case study.

<table>
<thead>
<tr>
<th>Defect type</th>
<th>Circumferential length (°)</th>
<th>Radial depth (mm)</th>
<th>Axial length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real corrosion</td>
<td>360</td>
<td>Nonuniform (0.01–1.3)</td>
<td>Nonuniform (59 ± 5)</td>
</tr>
</tbody>
</table>

![Fig. 17. The real gas pipe with a naturally developed corrosion.](image)

The profile of axial length of corrosion along the circumference.

![Fig. 18. The profile of axial length of corrosion along the circumference.](image)

Fig. 16(a) and (b) shows the reconstructed signals and the residual components after decomposing the original reflection signals for two defect cases respectively. It can be seen from Fig. 15 that the first reflection components (the decomposed front-edge reflections) are almost the same since these components primarily depend on the geometric profile of the start of the defect, including its depth and circumference which are the same for both defect cases. The amplitude of second reflection component (the decomposed back-edge reflection) generated by the 6 mm-defect is smaller than that of the back-edge signal generated by the 16 mm-defect. Hence, the real amplitude information related with the axial length of defects can be clearly presented from the decomposed back-edge reflection signals after the success of the decomposition process.

Because the waveforms of the front- and back-edge reflection signals present similar patterns in time domain, the time shift \( T_s \) between these two determined edge signals can be computed by using the cross-correlation function as defined in the following equation:

\[ T_s = \max \left( \frac{1}{T} \int_0^T S_1(t)S_2(t+\tau)dt \right) \]

6. Conclusions

This paper reports a method in the frame of matching pursuit decomposition with the optimized IRC-dictionary to evaluate the axial length of pipeline defect. The proposed method is based on the fact that the overall reflection signal generated at a pipeline defect is the interference between two edge-related reflection components in a complicated manner. The method allows for not only an efficient reconstruction of defect reflection signal but also an accurate identification of the defect axial length through the clear identification of the primary front-edge reflection signal and the back-edge reflection signal. That is, the method can effectively resolve the closely spaced overlapping and noise-contaminated reflection components. Such task is difficult to achieve by using other conventional algorithms. Simulation tests and real experiments were used to verify the effectiveness of the method. The real experiments involve the use of in-servicing pipes that have artificial defects with different axial lengths as well as a corroded gas pipeline. The results show that the maximum errors in evaluating the axial extent are 2.69% and 6.34% for the in-servicing pipes and corroded gas pipeline respectively. Although
this paper focuses on the discussion on axisymmetric defect, for further research, we will focus on testing the method on more real pipelines that have complex defects.

**Acknowledgments**

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project no. CityU 122011) and a grant from City University of Hong Kong (Project no. 7008187).

**References**


