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Evaluation of pipeline defect’s characteristic axial length via model-based parameter estimation in ultrasonic guided wave-based inspection

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Abstract
The reflection signal from a defect in the process of guided wave-based pipeline inspection usually includes sufficient information to detect and define the defect. In previous research, it has been found that the reflection of guided waves from even a complex defect primarily results from the interference between reflection components generated at the front and the back edges of the defect. The respective contribution of different parameters of a defect to the overall reflection can be affected by the features of the two primary reflection components. The identification of these components embedded in the reflection signal is therefore useful in characterizing the concerned defect. In this research, we propose a method of model-based parameter estimation with the aid of the Hilbert–Huang transform technique for the purpose of decomposition of a reflection signal to enable characterization of the pipeline defect. Once two primary edge reflection components are decomposed and identified, the distance between the reflection positions, which closely relates to the axial length of the defect, could be easily and accurately determined. Considering the irregular profiles of complex pipeline defects at their two edges, which is often the case in real situations, the average of varied axial lengths of such a defect along the circumference of the pipeline is used in this paper as the characteristic value of actual axial length for comparison purpose. The experimental results of artificial defects and real corrosion in sample pipes were considered in this paper to demonstrate the effectiveness of the proposed method.

Keywords: pipeline inspection, guided waves, defect characterization, parameter estimation, Hilbert–Huang transform

(Some figures in this article are in colour only in the electronic version)

1. Introduction
The use of ultrasonic guided waves [1] is a new and advanced technique in the nondestructive testing (NDT) field. Thanks to its continuous development in both theory and applications, the guided wave technique has become increasingly attractive for inspection of defects in pipelines. For example, even defects (gouge, dent and material loss) that exist in underground pipelines can be successfully detected by the guided wave technique as reported by Ahmad et al in their experimental work [2]. The location of a pipeline defect can be determined by the arrival time of the reflection signal that results from the interaction of propagating guided waves with a defect. However, after a defect has been found, evaluation of its dimension or size is always a challenging task in NDT [3]. That is, although the reflection signal in principle includes
substantial defect information related to size and other features of the defect, it is usually rather difficult to interpret this signal for defect characterization or sizing because of complexities of the interaction process. The utility of guided waves is thus limited by the lack of detailed information on the detected defect. For further assessment of the defect’s features, for example its severity, additional testing with the help of other methods or direct measurement is then required. To accurately and efficiently carry out planned maintenance operation and replacement of defective pipelines, the ability of defect characterization during pipeline inspection is very important in practical application of the guided wave technique, particularly for defects that exist in parts of a pipeline that are difficult to access.

Most of the methods currently available for inspection of pipelines are only capable of providing a qualitative assessment of defects. Few research works have been conducted on the possibility of using guided waves for evaluating the size of pipeline defects. Reported methods for this problem can loosely be classified into two groups: one is to optimize the specific parameters of excited guided waves or construct a sophisticated configuration of the transduction system so as to achieve well-defined or -controlled waveform of reflection. The methods in this group can maximize the energy of the concerned wave signals and at the same time simplify them for facilitating possible sizing of the defect. Mu et al [4] determined the circumferential length of a pipeline defect by comparing theoretical reflection profiles with experimental ones obtained through performing a circumferential focusing scan at the known defect location. Li [5] developed an algorithm based on two-dimensional blind deconvolution to estimate circumferential sizes of defects using the multiple reflection waveforms acquired by a multiplexed circumferential transducer array. These methods require a great deal of care in transduction; considerable time may have to be spent increasing precision and reliability of instrumentation and checking repeatability of measurements. Methods in the other group make use of generally simpler and less specific instrumentation but need greater analysis of the obtained reflection wave signal for defect characterization. Such methods can decrease the complexity of required instrumentation so that practical applications become convenient. However, the processing of waves implies more difficulties due to the more complicated process of interaction of guided waves with different types of defects. Advanced signal processing techniques are needed to increase the probability of success in defect characterization and to ensure ease of practical application. For this motivation, Demma [6] investigated the effect of defect parameters on the reflection so as to enable a more precise interpretation of a reflection signal for evaluating the defect size. Recent advances include utilization of imaging and tomography techniques for defect characterization. For example, Hayashi [7] developed a defect image technique by reconstructing spatial waveforms that have been separated into several single-mode signals. A review of available methods for defect sizing or characterization can be found in [3] as well. Although these techniques have proved to be successful in various degrees, they are generally time/cost consuming and the results may be insufficiently accurate. Moreover, they still have not solved the problem of directly evaluating the axial length of pipeline defects.

2. The interference phenomenon of two reflection components

It has been found by some researchers that reflection of guided waves from a defect primarily results from the interference between the two reflection components generated at the front edge and the back edge of the defect [6, 8, 9]. Further we have reported in our earlier research [10] that the complexity of the reflection signal is essentially a result of different features represented by front-edge and back-edge reflection components. In previous studies, researchers mainly used simplified models, such as a notch or a circular hole, to approximate a pipeline defect. Realistic defects like corrosion are far more complex and irregular in three-dimensional profiles. Demma indicated in [11] that maxima and minima of reflectivity resulting from the interference of two reflection components could occur on real defects without a sharp and rectangular profile in practical inspection. Ma and Cawley further employed a part-thickness taper elliptical defect model to represent a closer match to real corrosion shapes in their latest research [12] for investigating the effect of different defect parameters on reflection. Their research showed that the reflection ratio spectrum from a complex defect still exhibited periodic patterns due to interference between reflections from the two edges of the defect. Thus, all of these findings suggest that the reflection signal from even a complex defect mainly consists of reflection components from the two edges of the defect, and the respective contributions of different parameters of the defect to the overall reflection can be represented by the features of these two reflection components. Identification of these components embedded in the reflection signal is therefore useful in characterizing the concerned defect.

The concept of applying the two primary edge reflection signals for defect characterization can be further explained as follows. The occurrence of reflection is due to the change of acoustic impedance in the structure. When the excited guided waves propagate to the locations of either the front edge or the back edge of defect, the acoustic impedance undergoes a fundamental change, which results in the occurrence of two strong reflection components. The defect area inside two edges can also generate reflections in the axial direction, but those reflections are generally negligible due to the small change of impedance within the defective area. Further, the small reflection is not observable because of energy attenuation after the waves propagate back to the transducer position. Irregularity of a defect in the circumferential direction inevitably makes the reflection signal at each edge of the defect complex. This complexity of the signal can be reduced by use of specific transduction. For example, in our experiments, the length-expander type of transducers were axially symmetrically distributed around the circumference of the pipe being tested and the signals received at all transducers were summed up, which can ensure
the maximal receipt of energy of waves propagating in the axial direction while other waves are ignored. When waves propagating to the defect can form a normal incidence at some region of the defect edge, especially a region with a large radial depth, the strong energy of reflected waves will be primarily concentrated in the axial direction and maximally collected by the length-expander transducers in axially symmetric distribution. Comparatively, other reflection processes are subject to attenuation of propagation or ignorance of a transducer, so the effects of these reflection components on the overall reflection signal are not significant. Moreover, each collected edge reflection signal is the result of reflections caused at all points of the defect edge. The profile of a practical defect in three-dimensional directions is gradually developed instead of a profile showing sharp or sudden variances, which implies high probability of two primary reflection components being generated in the process of interaction of guided waves with the defect.

Because of the presence of the interference phenomenon caused by two reflection components, the resulting reflection signal is seriously affected by the axial length of the defect. Therefore, identification of edge reflection components embedded in the overall reflection signal is useful for simplifying analysis of the interaction process and enabling defect characterization. Considering that the distance between two reflection positions at the defect edges closely relates to the axial length of the defect, the identified reflection components can help determine the axial length. Therefore, in this paper, we propose a method based on parameter estimation with the aid of an advanced signal analysis technique as a preprocessor for the purpose of reflection decomposition to enable defect characterization. This could efficiently decompose a noise-contaminated reflection signal into its primary components that correspond to the two edge reflections in guided waves-based measurement. The identified edge reflection signals can then be used for evaluating the axial length of the pipeline defect. In practice, for an irregular defect, ‘front edge’ and ‘back edge’ refer to the two boundaries between the defective and the non-defective areas of the pipeline body. Considering the irregular profiles of complex pipeline defects like corrosion at two edges, the average of varied axial lengths of such defects along the circumference of the pipeline is used as a characteristic value for representing the actual axial length. It can to a certain degree reflect all factors that have effects on the edges and the corresponding axial lengths of defects. A comparison of results from the proposed method and the actual experimental measurement is presented to verify the effectiveness of the findings of this work.

The rest of this paper is structured as follows. In section 2, the experimental setup and data collection are described. Section 3 presents formulation of the concerned problem and describes the proposed method in detail. In section 4, the proposed method is applied to the experimental data and the results are discussed. A conclusion is given at the end.

Figure 1. Illustration of varying axial lengths of the pipe defect under examination.

3. Acquisition of guided wave reflection signals

As aforementioned, the axial length of a defect is a critical factor that causes the complexity of the reflection. In order to investigate and establish the relationship between the edge reflections and axial length of a pipeline defect, and to further validate the method proposed in this work, a series of experiments were performed to collect reflections of guided waves created by artificial defects with varying axial lengths in pipeline samples. The focus of this paper is to present the method of evaluating defect length through considering edge reflection components. Therefore, although the motivation of the paper was related to industrial inspection tasks, to simplify mechanical processing of defects and clearly clarify the principle of the proposed method, only circumferential defects are discussed in this paper.

The first group of experiments was conducted on a steel pipe that had an external diameter of 34 mm, a wall thickness of 4 mm and a length of 2030 mm. We introduced artificial notches in the sample to simulate defects, radial depth and circumference of which were kept constant at 21.25% of the pipe’s wall thickness and 100% of circumference, respectively. Over the course of the experiments, the values of axial length were gradually increased from 6 to 170 mm using a milling machine to simulate defects of varying axial lengths, which is illustrated in figure 1.

We adopted the longitudinal L(0, 2) mode for excited waves as it is easy to excite and has a relatively simple acoustic field [13]. The L(0, 2) mode has roughly uniform stress distribution over the cross-section of the pipe, which makes it sensitive to changes in the cross-section of the pipe. Therefore, it is favored for detecting circumferentially aligned defects in hollow pipelines discussed in this paper. It is noted that for defect characterization in real operating environments where the pipeline may be covered by soil and filled with fluid, the wave mode needs to be carefully selected such that strong reflections are generated to maximize the effectiveness of post-processing for characterizing the defect. Frequencies ranging from 0.1 to 0.24 MHz were chosen in this paper for the pipe under examination because the L(0, 2) mode excited accordingly is non-dispersive in this frequency range. Figures 2(a) and (b) display phase and group velocity dispersion curves, respectively. Within the above-selected frequency range shown in figure 2, velocity values remain almost constant with only small variations. These curves were calculated using the DISPERSE program [14]. The use of the single L(0, 2) mode and the non-dispersive operating frequency range makes the reflection signals as simple as possible, relieving the burden of subsequent analysis.

3
The experimental setup and instruments used are depicted schematically in figure 3(a). A Hamming windowed toneburst consisting of five cycles at the chosen frequency was delivered through an arbitrary signal generator. It is formulated as follows:

\[ s(t)_{\text{excitation}} = \sin(2\pi ft)(0.08 + 0.46(1 - \cos(2\pi ft/5))). \]  

The temporal waveform of such an excitation and its FFT spectrum are shown in figure 3(b). The measurement system was carefully designed to excite a single L(0, 2) mode into the pipe under examination. A ring consisting of a certain number of piezoelectric transducers (PZTs) was bonded to one end of the pipe to generate and receive guided waves. The PZTs were made of length expander-type piezoelectric material and distributed axisymmetrically, thus ensuring that only the longitudinal modes were excited while the undesired flexural modes were suppressed.

Figure 4 shows the collection of signals reflected from some defects with varying axial lengths under excitation at center frequencies of 175 kHz. It is clearly observed that when the axial length of each reflection signal is changed, its waveform is extended in time with an increased number of wave cycles and distorted amplitude under irregular variations. For example, some of the signals in this figure exhibit the superposition effect, whereas others represent the cancellation effect. As indicated before, the complexity of these signals is the result of the interference caused by reflections at different edges of the defect. A certain amount of noise that follows the main signal sequence in figure 4 is due to multiple reverberations of reflections between two edges of the defect.

In order to further verify the effectiveness of the proposed method on complex pipeline defects, the test using the same transduction set-up as shown in figure 3 was conducted on a real gas pipe. The pipe was provided by a natural gas supplier in Hong Kong and it had a naturally developed corrosion, a commonly occurring defect type in the field. The pictures of pipe and corrosion are shown in figure 5. The pipe was originally located underground in operation and was covered completely by soil. Appropriate stresses exerted on pipes due to the result of soil movement, thermal contraction or third party interference can cause circumferential damage to coating or pipe body [15], especially in small diameter pipes. Due to adverse soil environment of high humidity and salinity in Hong Kong, pipes suffer further surface corrosion after the protective coating is damaged. Corrosion starts at the outmost surface

Figure 2. (a) Phase velocity dispersion curves; and (b) group velocity dispersion curves derived based on the properties of the examined pipe.

Figure 3. (a) Schematic representation of the experimental setup; and (b) the excited tone burst signal and its FFT spectrum.
Figure 4. Examples of reflection signals from defects with different axial lengths.

Figure 5. The real gas pipe with naturally developed corrosion.

of the pipe and gradually extends to other parts. The largest corroded area is thus at the outer surface of the pipe.

The tested gas pipe had an external diameter of 88.6 mm and a wall thickness of 5 mm. The corrosion distributed along the circumference of the pipe had a nonuniform axial length of $59 \pm 5$ mm. Detailed information on this corrosion is given in table 1 and the profile of the axial length of the corrosion along the circumference is also plotted in figure 6. Figure 7 shows the raw reflection signals collected from the tested pipe. The toneburst signal at center frequencies of 110 kHz was chosen as the excitation for this testing based on the dispersion curves of the tested pipe. The group velocity of propagating guided waves in the pipe was 5.4 m ms$^{-1}$. It is to be noted here that the use of higher frequency may reduce or avoid the interference of reflection components, but the energy of reflection signals will thus be greatly attenuated, resulting in difficulty in accurate defect characterization.

Table 1. Description of the real corrosion tested in the case study.

<table>
<thead>
<tr>
<th>Defect type</th>
<th>Circumferential length (deg)</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>

4. Proposed method for evaluating the axial length of defect

4.1. Problem formulation

As noted earlier, the reflection signal from a defect includes two primary components, i.e. the ‘front-edge signal’ and the ‘back-edge signal’ as illustrated in figure 8(a). Reflections from front edge and back edge of defect are reflections from hard boundary and soft boundary, respectively, so the phase
Figure 6. Profile of the axial length of corrosion along the circumference.

of the front-edge signal is the reverse of that of the back-edge signal. Both signals exhibit nearly the same patterns in terms of frequency, cycle number and modulation, but are different in phase. If they could be decomposed and correctly recovered to their original temporal waveforms, then the axial length of the defect will be easily evaluated. This is because the axial length is related to the distance between reflection positions of two edge reflection signals. The axial length can be derived based on wave group velocity and time shifts of the two reflection signals. Traditional methods like linear filters are ineffective for such decomposition because the two reflection signals present the same spectrum in the frequency domain but their amplitudes and phases are unobservable in the time domain.

It is apparent in figure 8(b) that there exist two non-overlapping regions and one overlapping region in the simulated reflection signal. The non-overlapping regions (1) and (2) correspond to partial observation of front-edge and back-edge signals, respectively. Therefore, the basic idea of signal decomposition proposed in this paper is based on estimation of an edge reflection signal from the data in the non-overlapping region. The front-edge signal is relatively simpler to determine compared to its back-edge counterpart because the former depends primarily on the front edge of the defect only, and it reaches the transducer position the earliest among all reflection components caused by a defect. In contrast, the back-edge signal is related to a larger number of factors and its rear is subjected to distortion due to reverberations between the two defect edges. Hence, we exploit the partial data of the front-edge signal in the maximum likelihood estimation (MLE) framework to resolve two overlapping signals. In pulse-echo ultrasonic guided wave-based measurement, the signal reflected from the defect edge can be modeled in the form of excitation integrated with the effect of dispersion and attenuation of involved guided waves. The mode considered in our study works within its non-dispersion frequency range (0.1–0.24 MHz), which allows the effect of dispersion to be neglected in the proposed reflection model.

4.2. Description of the proposed method

As described above, partial data of the front-edge signal, which corresponds to the non-overlapping region (1) shown in figure 8(b), is used to estimate the front-edge signal. Therefore, the first crucial problem is to determine the overlapping points of front-edge and back-edge signals so that the non-overlapping region (1) could be identified. As mentioned in the previous section, front- and back-edge signals have a certain phase difference but the same frequency spectrum. Hence, instantaneous frequency discontinuity will
appear at the overlapping points of the two signals. Such a discontinuity can be indicated by the abrupt change of the frequency value in the form of a higher order derivative in time–frequency representation of the reflection signal. The concerned discontinuity points, i.e. overlapping points of the two edge signals, can be accordingly determined. The collected reflection signal is inherently susceptible to noises caused during propagation and interaction of guided waves in the pipeline. Moreover, traditional signal processing methods may be inadequate for analysis of complicated nonlinear and non-stationary guided waves. In order to reveal hidden reflection signals in the collection and to provide a precise definition of partial data of a front-edge signal for the proposed estimation context, the Hilbert–Huang transform (HHT) method is used as a preprocessor to reconstruct the required data from the collected raw reflection signals.

HHT is an empirically based data-analysis method proposed by Huang et al. [16] to efficiently obtain information in both time and frequency domains directly from the data. It is adaptive, automatic, efficient and without any prior assumptions. The HHT consists of two parts: empirical mode decomposition (EMD) and Hilbert spectral analysis (HSA). EMD can be treated as a time–frequency filtering method for decomposing the signal into a collection of intrinsic mode function (IMF) components. The detailed theory and procedures to derive and compute IMFs can be found in [16, 17]. The collected raw reflection signal \( s(t) \) is then expressed as the sum of IMFs (IMF\(_i\)) and a residue \((r_{n+1})\), as defined in the following:

\[
s(t) = \sum_{i=1}^{n} \text{IMF}_i + r_{n+1} \quad (i = 1, \ldots, n). \tag{2}
\]

Each IMF is a unique band-limited function and different IMFs exhibit different frequencies at the same time. Some extracted IMFs belong to noise-related components identified with the aid of frequency spectrum analysis and correlation analysis of all IMFs. In our application, proper IMFs constituting edge reflection signals should contain frequency components \((fc)\) close to the center frequency \((175\text{ kHz})\) of an excitation toneburst signal. Moreover, the decomposition procedure of EMD may introduce aliasing in IMFs. Hence, the correlation coefficient \((cc)\) between the proper IMF and the excitation signal should have a large value. Based on these two criteria \((fc\text{ and } cc)\) for evaluating IMFs, proper IMFs can be discriminated from the original data to reconstruct the actual reflection signal \(s'(t)\) for subsequent analysis:

\[
s'(t) = \text{IMF}_a + \text{IMF}_b + \cdots \text{IMF}_z \quad (a, b \ldots z \in i). \tag{3}
\]

After obtaining the reconstructed signal, the easiest way to compute its instantaneous frequency is by performing the corresponding HSA, through which the relevant complex conjugate \(u'(t)\) of any real-valued function \(s'(t)\) can be determined by

\[
u'(t) = s'(t) = H(s') = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{s'(\tau)}{t - \tau} d\tau. \tag{4}
\]

The signal for the concerned time–frequency analysis can then be constructed from the input signal \(s'(t)\) and its Hilbert transform \(u'(t)\) as

\[
A(t) = s'(t) + iu'(t) = a(t) e^{i\theta(t)}, \quad \text{and} \quad \omega = d\theta/dt \tag{5}
\]

where \(a(t)\) is the instantaneous amplitude, \(\theta(t)\) is the phase function and \(\omega\) is the instantaneous frequency. The abrupt change of instantaneous frequency in the form of knee points will be displayed clearly in the result of time–frequency analysis of the reflection signal \(s'(t)\). That is, the first overlapping point of the two edge signals and partial observation data \(s_{a1}(t)\) in the non-overlapping region (1) can be efficiently identified.

Resolution of the two edge signals is achieved from the model-based parameter estimation perspective. In experiments conducted for this research, the signal reflected from an edge of the defect can be described by using a parametric signal model, which is the time-delayed and amplitude-scaled replica of the excitation toneburst signal as given by equation (1):

\[
s(p; t) = a_1 \sin(2\pi f_1 t + \beta_1) \\
\times (0.08 + 0.46a_2 (1 - \cos(2\pi f_1 t/5 + \beta_2)))
\]

\[
p = [a_1 \quad f_1 \quad \beta_1 \quad a_2 \quad \beta_2]. \tag{6}
\]

The parameter vector \(p\) of the edge signal includes the amplitude \(a_1\), the center frequency \(f_1\), the phase \(\beta_1\), the window function amplitude coefficient \(a_2\) and the window function phase \(\beta_2\). The vector \(p\) is estimated from the identified partial observation data \(s_{a1}'(t)\) so that the whole front-edge signal can be determined. This parameter estimation problem is achieved by using the maximum likelihood estimation (MLE), a common statistical method for fitting a statistical model to data, and providing estimation for parameters of the model. The MLE for the vector parameter \(p\) is defined as the value that maximizes the likelihood function \(L(p)\), now a function of components of \(p\) for estimation. The likelihood function is usually defined as the joint probability density function (PDF) of the observed data with respect to the parameter vector \(p\), which obeys normal distribution assuming that the data are independent and identically distributed (iid):

\[
\text{PDF}(s(x); p) = \frac{1}{2\pi^{n/2} |\Sigma(p)|^{1/2}} \exp \left\{ -\frac{1}{2} (x - m(p))^T \Sigma^{-1}(p) (x - m(p)) \right\} \tag{7}
\]

where \(m(p)\) is the mean vector, \(\Sigma(p)\) is the covariance matrix and \(n\) is the dimension of the considered signal \(s_{a1}(x)\). For the case of \(s_{a1}'(x)\) with constant parameter vector, the problem of maximizing the PDF can usually be simplified to minimizing the least-square function (LSF) defined as

\[
\hat{p} = \arg \max \text{PDF}(p) = \min \sum_{i=1}^{n} (s_{a1}'(x_i) - s(p))^2 = \min \|s_{a1}'(x_i) - s(p)\|_2. \tag{8}
\]

The minimum values of the above objective function will provide the optimal solution for parameters being estimated. That is, the optimal MLE of the parameter vector \(\hat{p}\) can be determined by considering only the partial observation data.
and back-edge signals. Therefore, the axial length of the defect can be calculated as twice the evaluated axial length of the defect, namely twice the evaluated length of the defect from the constructed reflection signal. Since front- and back-edge signals present similar patterns in the time domain, the time shift $D$ between these two signals can be computed by using the cross-correlation function (CCF). With this method, the time shift $D$ between the two signals corresponds to the maximum value of their CCF, as shown below:

$$D = \max \left( \frac{1}{T} \int_{0}^{T} -x(t)y(t+\tau)\,d\tau \right),$$

where $T$ is the observation time, $x$ and $y$ are identified front- and back-edge signals. $D$ corresponds to the time the guided waves take to propagate between front and back edges of the defect, namely twice the evaluated axial length of the defect.

Therefore, the axial length of the defect can be calculated as

$$L = (D \times v_{gr})/2,$$

where $L$ is the evaluated length of the defect in the axial direction and $v_{gr}$ is the group velocity of the propagating guided waves.

In summary, the proposed method for evaluation of the axial length of pipeline defects comprises the following six steps:

- **S0**: use EMD to decompose the collected raw signal $s(t)$ into a collection of IMFs;
- **S1**: select the proper IMFs to reconstruct the reflection signal $s'(t)$ based on two criteria ($f_c$ and $cc$);
- **S2**: perform HSA to determine the overlapping points and the data $s''_q(t)$ in the un-overlapping region of the front-edge signal;
- **S3**: take $s''_q(t)$ as observation to estimate the signal parameters $\hat{p}$ and then identify the front-edge signal $\hat{x}(t)$;
- **S4**: obtain the back-edge signal $\hat{y}(t)$ by subtracting the front-edge signal $\hat{x}(t)$ from the constructed reflection signal $s'(t)$, i.e. $\hat{y}(t) = s'(t) - \hat{x}(t)$;
- **S5**: evaluate the axial length $L$ of the defect from knowledge of the obtained front-edge signal $\hat{x}(t)$ and back-edge signal $\hat{y}(t)$.

### 5. Application results and discussion

Firstly, performance of the proposed method is illustrated by evaluating an artificial notch-type defect with the axial length of 18.5 mm in guided wave-based inspection. Reflection data of this defect were already collected in the first group of experiments described in section 3. Figure 9 shows the raw reflection signal collected from the pipe with this defect. Compared to the excitation toneburst signal, it exhibits an increased cycle and distorted amplitude due to the interaction process and kinds of noise. This case is used to demonstrate the validity of our method for evaluating the axial length of the pipeline defect.

The EMD is first applied to decompose the collected reflection data into a series of IMFs. The results are shown in the first column of figure 10. The frequency spectrum of each IMF and its correlation coefficient with the original excitation signal are presented in the second column of figure 10 and table 2, respectively. The eight IMFs yielded by the EMD procedure show the variation (from high to low) in their frequencies. It is apparent that only IMF5 and IMF6 have frequency components close to the center frequency of 175 kHz of the excitation signal. Other IMFs have either higher or lower frequencies. They are assumed to be caused by different sources of noise. Analysis of the correlation coefficient of each IMF further demonstrates that IMF5 and IMF6 have high $cc$ values (0.7914 and 0.3409) compared to other IMF components. Therefore, the defect reflection signal is reconstructed to be IMF5+IMF6, which is shown in figure 11.

The frequency–time representation of the reconstructed signal based on the HSA is presented in figure 12. It shows that two obvious frequency discontinuities exist. One

### Table 2. Correlation coefficients for all signal components decomposed from the reflection signal.

<table>
<thead>
<tr>
<th>Signal component</th>
<th>IMF1</th>
<th>IMF2</th>
<th>IMF3</th>
<th>IMF4</th>
<th>IMF5</th>
<th>IMF6</th>
<th>IMF7</th>
<th>IMF8</th>
<th>RES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficient</td>
<td>0.0223</td>
<td>0.0228</td>
<td>0.0145</td>
<td>0.0103</td>
<td>0.7914</td>
<td>0.3409</td>
<td>0.0559</td>
<td>0.0027</td>
<td>0.0040</td>
</tr>
</tbody>
</table>
Figure 10. Decomposed components of the raw reflection signal and their FFT spectra after applying EMD to this signal.
Figure 10. (Continued.)

Figure 11. Reflection signal reconstructed with EMD.

Figure 12. HSA representation of the reconstructed signal with two knee points identified.

is at $(0.0005185, y_a)$ and the other at $(0.0005478, y_b)$. They correspond to the overlapping points of front-edge signals and back-edge signals. From figure 11, the start time for the reconstructed signal is directly known to be 0.0005085. Hence, the non-overlapping region of the front-edge signal can be easily determined as $[0.0005085, 0.0005185]$. Reconstruction of the reflection signal and determination of valid observation data through HHT are greatly helpful in accurately estimating the concerned signal parameters for defect characterization.

The signal segment in the range of $[0.0005085, 0.0005185]$ is then extracted from the reconstructed reflection signal to form the partial observation vector of the front-edge signal for estimation of its parameters, shown in figure 13. Based on the information of the excitation toneburst signal in the conducted experiment, the initial guess $[-0.5, 175000, 0, -0.5, 0]$ is provided for the parameter vector of the front-edge signal in the estimation algorithm. The value $-0.5$ is used for the amplitude considering the attenuation effect of guided waves in propagation and phase reversal of propagating waves at the front edge of the defect. The value 175000 is used because the center frequency of the excitation toneburst signal is 175 kHz. The minimization of equation (8) with a termination tolerance of $1 \times 10^{-8}$ used toward the proposed edge reflection model provides the optimal solution of estimated parameters. The finally obtained signal parameters are $[-0.031983, 161190, 13.173, -4.9659, -9.2036]$. That is, the amplitude is estimated to be $-0.032$, center frequency $161.12$ kHz, phase $13.173$, window function amplitude $-4.9659$, and window function phase $9.2036$. The estimated signal is plotted with a dotted line together with the observed signal as a solid line for comparison in figure 14. It shows that excellent agreement is achieved between the two signals.

With successful estimation of the concerned parameters, the front-edge signal can be produced based on the reflection model as represented in equation (6). The result is shown...
Figure 14. Partial data of the observed front-edge reflection signal and its estimation.

in figure 15(a). The back-edge counterpart can further be extracted from the reconstructed reflection signal as shown in figure 15(b). The evaluated axial length of the defect can then be calculated by using the CCF method. Alternatively, since the front-edge signal and back-edge signal have phase reversal, the time shift between these two signals can be determined with the distance between the lowest peak of the front-edge signal and the highest peak of its back-edge counterpart. That is, the axial length \( L \) of the defect can be calculated as

\[
L = (P_H - P_L) \times \frac{v_{gr}}{2} = (5.3245 \times 10^{-4}
- 5.2519 \times 10^{-4}) \times \frac{5.35}{2} = 19.4 \text{ mm},
\]

(11)

where \( P_L \) and \( P_H \) are the lowest peak of the front-edge signal and the highest peak of the back-edge signal, respectively. This indicates that the axial length of the defect evaluated by using the proposed method is very close to its actual measurement. The results of additional tests on defects with other axial lengths are listed in table 3. They also demonstrate that the proposed method can provide good performance in evaluation of the defect’s axial length, especially for the defects under serious conditions. The method can be optimized through introducing new techniques of parameter estimation when the defect is very small so that the limited partial data used for parameter estimation can guarantee sufficient estimation performance.

Figure 15. The obtained (a) front-edge signal; and (b) back-edge signal.

Figure 16. The reflection signal generated by real corrosion that exists in the real gas pipe.

Performance of the proposed method is further demonstrated by evaluating the axial length of real corrosion in the gas pipe shown previously in figure 5. Figure 16...
presents the collected signal reflected from the real corrosion. This reflection signal was reconstructed through the EMD procedure, and the result is presented in figure 17. The frequency–time representation of the reconstructed defect reflection is shown in figure 18(a), in which the first overlapping point (0.000295, \( y_a \)) and the non-overlapping region of the front-edge signal \([0.00027, 0.000295]\) could be accordingly determined. Parameter estimation was performed on extracted partial observation data and the finally obtained result was \([-0.00015797, 0.000295, -8.5537, 575.99, -1.1354]\). The front-edge signal and back-edge signal can be further produced, as shown in figures 19(a) and (b), respectively. The evaluated axial length of corrosion can be calculated based on equation (11) as

\[
L = (P_H - P_L) \times v_{gr}/2 = (3.1408 \times 10^{-4} - 2.9178 \times 10^{-4}) \times 5.4/2 = 60.21 \text{ mm.}
\]

Compared to the notch type of defect considered in the first group of experiments, the corrosion type of defect in this testing has irregular profiles at its two edges. As mentioned in section 3, the length of corroded area is measured to be \(59 \pm 5\) mm along the axial direction of the pipe. The average of varying axial lengths of corrosion along the circumference of the tested gas pipe is used as the characteristic value for representing the actual axial length of this corrosion. The value (60.21 mm) of the axial length evaluated by using our method proved to be close to the characteristic value (59 mm) of the real axial length, which indicates that our method can also efficiently provide useful information of complex pipeline defects. It is noted that the effectiveness of the proposed method can be particularly well presented by the considered corrosion case, while other more complex defect cases need further investigation.
6. Conclusion

This paper proposes a method to evaluate the characteristic axial length of defects in pipelines. The evaluation makes use of the fact that the overall reflection signal generated at the defect is the interference between two primary reflection components, one from the reflected signal related to the front edge of the defect and the other from the reflected signal related to the back edge of the defect. The evaluated axial length of the defect bears a direct relationship to the relative distance between reflection positions at the two edges of the defect, which is further closely related to the phase information of the two edges’ reflection signals. With the proposed method, the front-edge signal can be determined from a parametric model-based estimation procedure with the aid of HHT as a signal preprocessor, which further enables decomposition of back-edge signals from the collected reflection data. That is, this method provides an effective tool to resolve the closely spaced overlapping reflection components, which is difficult to achieve by using other conventional algorithms because the involved signals exhibit the same patterns except the time phase. Once the two reflection signals have been decomposed and identified, an axial length of the defect can be easily evaluated. For complex defects with irregular shapes, since two primary reflection components are generated in the interaction process of guided waves with defect as explained in section 2, the axial length of such defects can still be evaluated through two edge reflection components that represent characteristic information related to the defect’s actual axial length. Verified against actual experiments with known defects including real corrosion, the results prove that our proposed method is effective in evaluating the characteristic axial length of pipeline defects in the discussed cases.

Another benefit of the method proposed in this research is that it can enable the evaluation of more defect parameters and further comprehensive defect characterization once two primary edge reflection components are identified. That is, each identified edge signal embeds geometric information of the corresponding edge of the defect, so the radial depth and circumferential extent or other parameters of the defect could be assessed by using proper component analysis techniques on the edge signals. This is another research work that will be reported in another forthcoming paper.

The current investigation is limited to circumferential defects in straight, empty pipelines. It is hoped that the method proposed in this paper will be generalized to more complex real cases, which concern arbitrary-shaped and localized corrosion defects in various operating environments. Further research is inevitably needed to improve the proposed method in future.

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