Semi-quantitative Analysis of Defect in Pipelines through the use of Technique of Ultrasonic Guided Waves

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Abstract. Modernized cities must have adequate infrastructures to support the daily needs from her citizens. The continuity in pipeline services that supply water, gas and oil to citizens and deliver wastes to designated collectors are in prime concern to any modernized city. However, in-service pipeline is prone to defects due to aging, external impacts, or hazardous operating environment. It is of prime importance to apply an efficient inspection method to characterize the potential defect in pipeline so that the information of damage caused can be determined prior to the fatal rupture of pipeline. An early warning generated from an accurate characterization of defect can encourage the performance of proper remedy and maintenance for minimizing the scope of damage to pipelines. In this paper, a presentation is given to an advanced inspection technique based on ultrasonic guided waves. This technique has already shown great potentials in non-destructive testing of material and structures in many fields. The advantages and difficulties involved in the pipeline inspection using ultrasonic guided waves have been identified. For the quantitative characterization of defect in pipeline inspection based on advanced guided waves, we propose the method through considering the reflected signal since it provides useful information related to defect. The method analyzes the captured signals reflected from the potential defect, decomposes the embedded dimensional information of defect and then accordingly identifies its severity. Although the experiments were conducted on artificial defects, the results proved that qualitative characterization of defect is feasible. Combined with guided waves, our method can provide comprehensive information related to the existence, location, severity of defect etc., through the analysis of reflected signal from the interactions of excited guided waves with pipeline defect.

Introduction

Pipeline is an essential infrastructure in any city for supplying and distributing water, gas, chemicals etc. to various households and industries. Due to the pipeline often buried or located in the areas with rugged environment, it is susceptible to various kinds of defects. If these defects cannot be found at early stage of development, then they may deteriorate to leak and eventually result in a fatal rupture that may cause huge economic loss and even human casualties. With the ever-increasing concern on safety and environmental protection, such defects in the pipeline are intolerable and unaffordable. In Hong Kong, 900 million cubic meter of water is supplied annually to citizens through a vast pipeline network of 7,200 kilometers, but at least 25% of the supplied water is lost in transit because of undesired seepage, costing Hong Kong taxpayers $700 million every year (Fig. 1(a)). A fatal explosion took place in Hong Kong on 11 April 2006, causing 2 death and 7 injuries, and seriously damaging the basement of a residential high building (Fig. 1(b)). The reason of the explosion was the leakage of gas from underground pipelines. Hence, there is always an urgent need to develop an effective and reliable pipeline inspection approach that can provide accurate identification of defects in pipelines and early warnings prior to fatal rupture.

Compared with other structures, many difficulties are involved in the inspection of pipeline due to its large and complicated three-dimensional structure. Currently, a number of techniques have been
developed to inspect in-service pipelines, such as the methods based on vision [1], acoustic [2], magnetic flux leakage [3] and eddy current [4]. When using these methods, a removal of insulation around the outside surface of the pipeline or mounting an instrument inside the pipeline may be needed. In addition, every point along pipeline must be scanned to collect sufficient data for a comprehensive analysis of the health of pipeline. Furthermore, nearly all conventional inspection techniques that are commonly used by public utilities are still based on a passive mechanism. That is, only when an existing defect grows to a certain stage of deterioration or until a major leak occurs, such techniques then become effective. Hence the conventional inspection methods are time consuming and labor intensive to be used, inefficient, and expensive to apply in practical applications.

In recent years, an active inspection method based on ultrasonic guided waves [5] has evolved. It shows great potentials in NDT for inspecting materials and structures of many fields. There are many advantages of using guided waves in pipeline inspection. First, it can travel over a long distance with high speed and low attenuation. Hence, it enables a line-to-line inspection method, makes it uniquely suitable for large and buried structure. Second, only a small hole is needed to be excavated from the buried soil so that a single transducer, which acts as an emitter as well as a receiver, can be positioned on the pipeline for inspection. Third, the entire cross section of pipeline can be covered as long as proper modes of guided waves have been selected and emitted. Forth, guided waves have a high sensitivity to interference or discontinuities exist along the propagation path, so various types of defects in pipelines can be detected. Therefore, the method of guided waves is expected to alleviate the aforementioned disadvantages of the conventional pipeline inspection techniques that are commonly used in public utilities and industries today.

In order to accurately carry out the planned maintenance and replacement operations of defective pipeline, the ability to characterize the defects, in the procedure of pipeline health monitoring or inspection is important for practical application of NDT techniques. Particular interest is on the detection of corrosion in pipelines as such defect is so common due to the humid and saline environment of Hong Kong (Fig. 1(c)). It is therefore necessary to carry out the advance signal processing and analysis on the inspection data for such purposes. The use of ultrasonic guided waves in the pipeline provides an attractive solution to the problem because they have a very high sensitivity and resolution. The returning reflection from the interaction of guided waves with defect will indicate the presence of defect and its other features. Through analyzing the result of interaction of guided wave with defect, useful information can be extracted and correlated to the parameters of defect so that a quantitative characterization can be achieved.

![Image](a)

![Image](b)

![Image](c)

Fig. 1. (a) The water leak blocked the traffic [9]. (b) The gas explosion that caused 2 deads and 7 injuries [9]. (c) The common defect in Hong Kong’s pipelines – corrosion.
Brief theory of reflection of guided waves at defect

The reflection signal usually includes useful information related to the defects interested. The reflection procedure of guided waves at defect can be characterized by the crossing of the discontinuity surfaces at two ends of defect, one of which is the cross section with falling edge and the other is one with rising edge. When the waves reach to the defect, part of the wave is reflected from and part of the wave is transmitted across two ends of defect respectively. The characterization of wave reflection at two defect ends is different considering the different acoustic impedance change at these ends. The relations among the involved waves in reflections can be described by the boundary conditions [6] shown as follow.

\[ p_i + p_r = p_t \] (acoustic pressure conservation) \hspace{1cm} (1)
\[ S_1(v_i + v_r) = S_2v_t \] (mass velocity conservation) \hspace{1cm} (2)

Where \( p_i, p_r, \) and \( p_t \) are acoustic pressures of emission waves, reflection waves and transmitted waves at defect respectively, \( v_i, v_r, \) and \( v_t \) are velocities of emission waves, reflection waves and transmitted waves at defect respectively, and \( S_1 \) and \( S_2 \) are cross sections on both sides of defect edge.

Experimental Setup

The experimental setup and the instruments used are shown schematically in Fig. 2. An arbitrary signal generator delivered a windowed toneburst signal to the ultrasonic pulser, which was then amplified to excite the PZT transducer for generating the desired incident guided waves. When the propagated waves met any discontinuity in pipeline they would be reflected and captured by PZT transducer, which were then delivered to PC for data processing through DAQ. A transducer ring consisting of certain number of piezoelectric elements was bonded at the one ending of inspected pipe for the transmission and reception of guided waves.

![Fig. 2. Schematic representation of experimental setup for the pipe inspection](image)

Experiments were conducted on the 34-mm external diameter, 4-mm wall thickness steel pipe. In order to simplify the investigated defect problem that can be usually described as the metal loss of pipe wall, we introduced an idealized fully circumferential notch in pipes as the simulated defect, which has an arbitrary depth in radial direction, arbitrary extent in axial direction. The values of these two parameters were gradually increased on a milling machine to simulate different defect degrees. The examined pipe sample was 2.03-m long and the simulated defect patch was machined initially at 1.3-m from the end where the PZT transducers were bonded. Two separated pipes were used to determine the effect of radial depth and axial extent for the resulted signal of reflection respectively. The relevant data were collected before introducing any notch to the pipes in order to obtain a reference. One experimental objective also includes the construction of correlation between the reflection features in the interaction and the geometrical parameters of the inspected pipe.
Fig. 3 shows the group velocity dispersion curves for the inspected pipe. The curves were calculated using the program of DISPERSE [7] and displayed with velocity (meter/ms) in the y-axis and frequency (MHz) in the x-axis. The use of the velocity curves is to identify which mode is more stable and easy to generate within a large frequency span. For instance, the longitudinal L(0, 2) mode at the frequency range of 0.12 MHz to 0.18 MHz was therefore selected because of the advantages of non-dispersive behavior, fast (at a higher velocity) propagation, and easy to be excited with the PZT. In order to excite the L(0, 2) mode, a transducer ring that consists of certain number of piezoelectric elements was bonded at one end of the pipe for generating and receiving guided waves. Each transducer element was made out of length-expander type of piezoelectric materials. The transducers were arranged in axisymmetric-spaced configuration in order to ensure that only longitudinal modes were excited whilst flexural modes were suppressed. It is because that the flexural mode is non-axisymmetric type and can only be generated in non-axisymmetric configuration.

Experimental Results and Discussions

A series of experiments were performed to investigate the behavior of reflected waves due to different extent of artificial defects for simulating the effect of different degree of severity. Fig. 4 shows two diagrams of typically received reflected signals with y-axis as the amplitude of the waves and x-axis as time. Only the longitudinal L(0, 2) mode is excited and observed in the echoes from the artificial defect and the ending of pipe. As shown in Fig. 4(a), the first pipe has an artificial defect with 1.1 mm radial depth and 3 mm axial extent. Whilst in Fig. 4(b), the second pipe has an artificial defect with 0.85 mm radial depth and 170 mm axial extent. Note that the reflected waves of the first pipe has higher amplitude due to the artificial defect has deeper radial depth. Whilst, the reflected waves in the second pipe shows much longer extent in time due to longer axial extent of the artificial defect.
Fig. 4. Typical received signals in the conducted experiment for pipeline inspection.

The experiments were conducted on the pipes with the artificial defects at various radial depths and various axial depths except the circumferential extent of pipe kept constant. The presence of artificial defect can be clearly indicated by the echoes appeared in unexpected places of captured reflected waves. The location of the artificial defect can be derived from the propagation time of each echo and the velocity of emitted waves. The interactions between the emitted guided waves and the artificial defect were further investigated to reveal the extent of the defect, such as depth and length of the defect. The results indicate that the reflected waves do provide valuable information on the radial depth and axial depth of the artificial defect.

**Effect of Radial Depth**

In order to study the effect of radial depth on the reflection of defect, the experiments were performed on the pipe with a notch that had a constant axial extent (close to zero) and varying radial depth. Fig. 5 shows the measured data corresponding to the echoes from the notch in various radial depths. The curve that indicates the correlation between the radial depth and the root-mean-square (RMS) of amplitude of reflection is presented in Fig. 6. It is clearly seen that the amplitude as well as the RMS value of reflected signal increase monotonically or roughly linearly with respect to the radial depth of defect at given frequency value (145 kHz). If the pipe parameters (such as material and dimension), other defect parameters except for depth, and excitation condition are changed, then the coefficients of reflection function may change slightly, but the trend of monotone increasing should be the same.

![Fig. 5. Collected signals of reflection from the notches that have various radial depths.](image1)

![Fig. 6. Variation of reflection ratio with various radial depths of notch at a frequency of 145 kHz.](image2)

**Effect of Axial Extent**

Another issue to be tackled is the investigation of the effect of axial extent for interaction of waves. The tests were performed on the pipe with a notch, the depth of which kept constant (around 21% of wall thickness) while the axial extent was gradually changed from 3mm to 170 mm. Fig. 7 shows that reflected signals from the notch with varying axial extents at 145, 175 and 200 kHz. It can be observed that with the increase of axial extent, the wave packet of reflected signal was extended in time (increased wave cycle number), and its amplitude showed an irregular change. These results indicate that axial extent is an important parameter affecting reflection. In addition, it is particularly interesting to observe the coincidence of wave pattern and amplitude in the beginning portion of signals corresponding to different axial extents. The longer the axial extent, the more the coincident of wave pattern and amplitude in the beginning portion of signals. This indicates that the resulting signal from the interaction of waves with defect may involve the superposition of two signals, which were resulted from the reflections at the start point (front end) and the end point (back end) of detected notch. The assumption was validated when the axial extent was long enough (170mm for our examined pipe samples). Two separated signals from two ends of notch were clearly observed in
time, which are marked with the arrows in Fig. 7. The first signal was resulted from the reflection at the front end of the notch. Based on this finding, some simple signal processing was applied to extract the reflected signal from the back end of the notch. Fig. 8 presents the results at 175 kHz frequency situations, showing that the cycle numbers in all reflections from the back end were kept constant, and amplitudes changed with the varying axial extents. The correlation between the amplitude change of the front/back end reflection and axial extent is presented to be a roughly periodical variation when notch length is expressed as a fraction of the wavelength of excitation.

Since the reflection from notch come from the interaction and superposition of two signals generated at the front and the back end of notch, it will be very useful for the defect inspection that these two signals can be separated out. Most of discussions on similar studies of interaction in the available literatures [8] mainly focus on the final overlapped signals. However, the interference of the separate reflections from the two ends of defect can be superimposed or cancelled for the resulting signal, thus it is not easy to directly identify the defect through the amplitude information of this signal. Instead, once the separated signals from two ends have been determined, the relative distance apart of the two reflection positions, which is directly related with the axial extent of notch, can be easily and accurately derived based on the wave group velocity and time shifting of two signals.

![Collected signals of reflection at the notch with various axial extents at 145, 175 and 200kHz respectively.](image)

The pattern and amplitude of reflection from the front end of notch were found to be same at all of the situations with various axial extents in the experiments. This is because the signal from the front end of notch (incident from a thick section to a thin section of pipe) mainly depends on the depth of defect, the effect of which for reflection has been discussed earlier. It has been defined that the main two peaks of the back end reflection occurred when the axial extents were about half and full wavelength of excitation waves. And it is also observed that these maximum peaks of back end reflection in the form of root-mean-square were very near to the reflection values at the front end of notch at all of three frequency situations. Except for these, the back end reflections generated at the other axial extent situation were small than the front end reflection. The interaction of guided waves with real defect is a relatively more complicated phenomenon due to the propagation in rough corroded area and reflection/refraction of waves at ends. The details about these problems, especially the reflection for a positive thickness change (incident from a thin section to a thick section) in
pipeline, still need further research to identify its physical mechanisms, especially the relation with wavelength and back end parameters of defect.

![Diagram of frontend and backend reflection](image)

**Fig. 8.** Separation of frontend reflection and backend reflection from experimental data.

**Conclusions**

Although intensive studies of guided waves on pipeline inspection have been conducting since the past two decades, there are still remaining many deficiencies that require continuous research efforts for further improvement. Currently, there is a significant technology gap with regard to the pipeline defect inspection, particularly in the identification of defect and its severity. Our experimental results show that the amplitudes of reflected signal increase monotonically with respect to the radial depth of artificial defect. When the axial extent is shorter than the length of the propagating wave cycles, the reflected front end and the back end signals of the axial extent will be overlapping, causing a misleading reflected signal pattern. Once, the overlapped signals have been separated based on holding the pattern of the front end signal remains the same, the true back end signal can be recovered. The different between the front and back ends signals provide the true time shifting value which is directly proportional to the true length of axial extent. The longer the axial extent, the more area the defect has occurred on the surface of the pipe.

Note that the results obtained from the experiments using the artificial defect could be different from the actual defect on an in-service pipe as the corroded area is usually uneven and irregular. Multiple reflections may be received. Nevertheless, the severe or large corroded areas can still appear as the largest reflection areas on the temporal plot. Although overlapping of signals may occur due to the existent of multiple corroded areas, the beauty of reflected guided waves is that the frequency and number of cycle of each reflected signal remains the same. Hence, by using our signal separation approach, we can separate each reflected signal or packet caused by each severe corroded area. Much research must be conducted to reveal the true phenomenon caused by defect which is a typical and major defect of buried pipeline. The study presented here can act as a solid foundation for future on-site tests using real corroded pipes. In future, with the helps from the ultrasonic guided waves and our analyses, the maintenance staff can obtain estimation on the severity caused by defect and the affected portion of the inspected pipeline. Based on the given information, the staff can decide
whether the affected pipeline should be shut down for an overhaul, and if the overhaul is required, the best time to perform the overhaul. Hence, fatal rupture and periodic shutdown of pipeline for unnecessary services, which may cause human causalities or blocking of traffic and waste of resources respectively, can be minimized.

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