

A Versatile Inspection System for Pipe Structure Using Ultrasonic Waves Propagation Imager

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Abstract. Pipe structure is vulnerable to many types of damage, such as flow-accelerated corrosion, crack, and in the case of multi-layers pipe, debonding damage. A versatile damage inspection system is needed, where it must be easily used for variety types of pipeline, must have the capability to detect many types of damage, as well as must be able to carry out inspection in the working condition of the pipe system. In this paper, we present the Ultrasonic Propagation Imager (UPI) that demonstrated to meet those demands. The UPI system consists of a high speed Q-switched laser, a high speed scanning mirror, a DAQ system, and a changeable sensing system depends on applications. Advanced signal processing using ultrasonic wavenumber imaging algorithm and energy mapping were applied for damage detection of the pipe structures.

1. Introduction

There are millions of kilometres of pipes around the world, transport various types of material, from water to oil and gas. Each application often required a specialized type of pipe, which different with each other in sizes, materials, and designs. From the perspective of an inspection engineer, such as from a pipeline manufacturer, this complexity poses a big challenging. An inspection system that designed to work well for one type of pipe does not necessary work for another. Therefore there is a need of a versatile inspection system that can be easily used for a variety types of pipeline, must have the capability to detect many types of damage, as well as must be able to carry out inspection in the working condition of the pipe system, and ideally obtain the inspection result in a short amount of processing time.

The system introduced in this paper answers some of those very demanding aspects. It is a damage inspection system based on guided wave technique. The research on guided waves using for damage detection has been around since the 60s and 70s, with a high expectation of becoming the paradigm shift of the structural health monitoring (SHM) for various structures, including the pipes structure. The high hope is mainly due to the capability of guided waves to propagate over a long distance from an excitation point [1]. Unfortunately that expectation has not yet been truly delivered in the sense that the guided waves techniques have not yet became the standard of the industry. The main limitation is that most guided wave SHM system relies on a very limited set of sensing and excitation points, which severely limits the ability to diagnose of the structure's condition. To fully investigate the structure,



we need a vast amount of data recorded the propagation of the ultrasonic waves of a very dense grid points on the structure. The technique that able to do that is so-called the full wavefield measurement technique. The ultrasonic propagation imager (UPI) system as showing here is one of currently three techniques that enable the measurement of full wavefield. The other two techniques are the scanning air-coupled transducer and the scanning laser vibrometer. Reader who interested in these techniques may refer to the recent review of Ostachowicz et al. [2].

This paper is organized as follows. We start with the introduction of working principle of the UPI system. Next, the algorithms for damage detection using the full wavefield are very briefly presented. Finally we show the applications of UPI for damage detection of a variety of pipes, with many types of damages and in at different working conditions of the pipes.

2. The Ultrasonic Propagation Imager (UPI) system

The principle of the UPI system relies on the reciprocity property of ultrasonic waves. The UPI uses one or many fixed sensing points and controls a Q-switched laser beam for scanning. Through reciprocity, a virtual laser ultrasonic wavefield is generated from the sensing point(s). This technique is applicable to realistic surfaces, in the sense that there is no need to prepare the structure's surface, unlike the scanning laser vibrometer technique. Also it allows for the manufacture of very high speed scanning systems. The latest generation of the Q-switched laser scanning system [3] has reached to scan speed of 20,000 points per second, which means that the inspection time for an area of $1\text{ m} \times 1\text{ m}$ with a spatial resolution of 1 mm is less than 1 minute. The inspected area can be extended using a set of electric-controlled mirrors to alter the direction of the laser beam.

Figure 1 shows the UPI system for measurement the full wavefield of a pipe specimen. The data of this test is one among several examples as we will show later in this paper. The distance between the laser scan mirrors to the specimen is about 2 meters, however it can be easily extended up to tens of meters using a laser beam collimator.

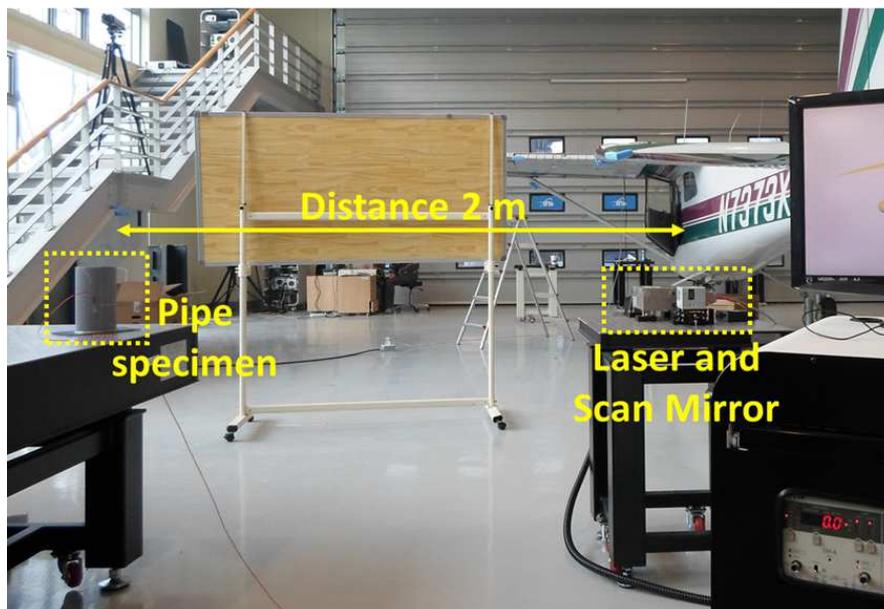


Figure 1. The Ultrasonic Propagation Imager (UPI) system

3. Algorithms for damage detection with full wavefield data

The essence of several algorithms for the processing of the full wavefield data used in this paper are presented. Readers who interests in detail may refer to the provided references.

3.1. Ultrasonic Wave Propagation Imaging (UWPI)

This is the basic algorithm that suitable for a preliminary inspection since it take very little computation and the result is in real time. The full scanning data forms a three-dimensional matrix $V \times H \times N$, where V and H represent the number of scanning points in the vertical and horizontal directions of the scanning area, while N is the sampling length of the measurement data for each scanning point. A slide perpendicular to the N axis maps the ultrasonic wave amplitude of the scan area at a particular time point. Plotting successive slides along the time axis generates a movie of ultrasonic waves propagation. A technician with some minimum training can analyse the wave propagation and able to give the assessment about the integrity of structure. If certain anomaly in amplitude or direction of the ultrasonic waves appears, further analysis with more complicated algorithms may needed for a stronger conclusive assessment.

3.2. Ultrasonic wavenumber imaging (UWI)

The main idea of the UWI algorithm [5] is as follows. The Lamb waves propagate across a thin plate at various modes. In the case when the plate has uniform stiffness, at one particular frequency of one particular mode, the guided waves have one corresponding dominant wavenumber. When the waves propagates across a damaged area, which has lower stiffness, the dominant wavenumber at that damaged area alters: increasing in the case of the A_0 mode and decreasing in the case of the S_0 mode. By mapping the dominant wavenumber at one particular frequency, it is able to detect the damages as well as estimate the damages size.

3.3. Waves energy mapping

The UWI algorithm only works with area-like damage, which means that it only can detect the damages with relatively large area: the damage size must be in the order of the ultrasonic wavelength. For the type of damage has at least one dimensions too small (slit-type or point-type), other algorithm such as waves energy mapping [6] can be used. The basic assumption of the waves energy mapping algorithm is that the wavenumber of the ultrasonic waves changes when the waves propagate through structural inhomogeneity such as geometry discontinuities or debonding. Therefore, by applying a narrowband wavenumber filter, and then calculating the waves energy of every spatial point in the scan area, it is able to visualize the damage areas.

4. Test specimens and analysis results

In this section, we will show the damage detection results of several pipe specimens. Since the target of this paper is to introduce a versatile damage inspection system, various types of pipes with various type of damages were chosen: plastic pipes with area-like damage, slit-like damage, and crack damage; steel pipe with slit-like damage; composite pipe with the debonding damage between two layers; and finally joint damage between two plastic pipes. Also, we will show that the UPI system is able to detect damage of the pipe even in working condition: with and without water inside the pipe. First, all specimens used for the test are shown in Figure 2 to 5, including description of structures and damages. Notice that figures 2a, 2b, and 2c show three plastic pipes with different kinds of damages: the flow-accelerated corrosion (FAC) damage, slit-type damages, and crack damages. Figure 3a shows the steel pipe before welding (which reveals the slit-like damages) and after welding. Figure 4a shows the picture and figure 4b shows the diagram of two plastic pipes joining together, but with an artificial

damages, as shown more clearly using two plane cut AA and BB. Finally, figure 5b shows the pipe with two layers: steel outside and plastic inside, with the debonding damage.

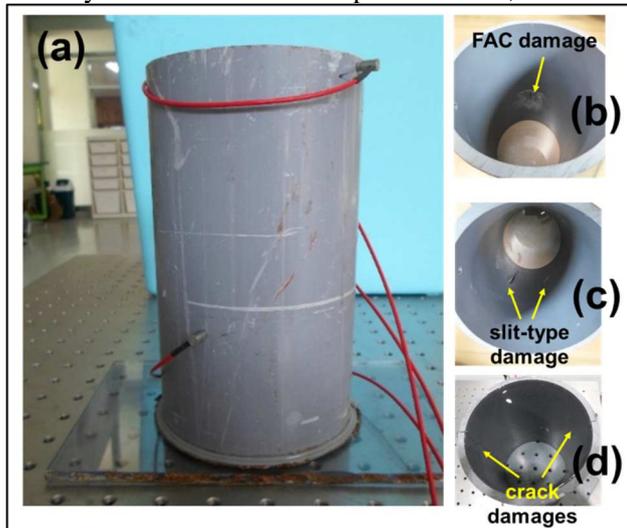


Figure 2. Plastic pipe with thickness 5.5 mm

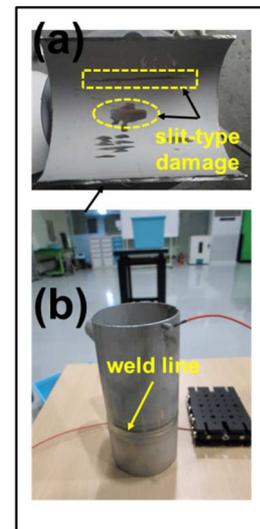


Figure 3. Steel pipe with thickness 2 mm

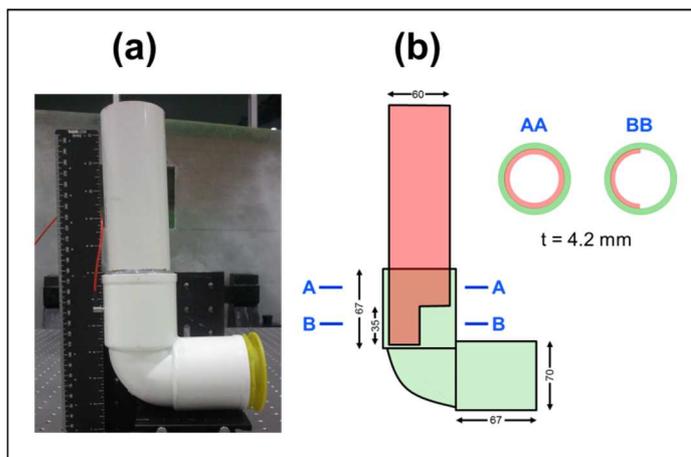


Figure 4. Plastic pipes joint with damage

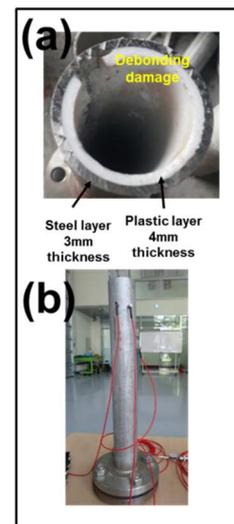


Figure 5. Composite pipe with debonding damage

4.1. Plastic pipe with flow-accelerated corrosion damage

The damage was made to simulate the damage that happens due to flow of liquid. Two cases were tested, with and without the water inside the pipe. Figure 6 and 8 show the damage detection result using UWPI and UWI, respectively. The presence of the water in the pipe can be easily visualize in the waves propagation in time domain with the appearance of the Scholte waves. Figure 7 shows the wavenumber frequency curves. Interestingly, even with the presence water, at the chosen frequency 150 kHz, the dominant wavenumber is still follows the same A_0 curve of the case without water. The size of the damage was estimated as in Figure 7. The damage size identified using UWI algorithm for two case: with and without water are approximately equivalent with the different of two dimensions is less than 3 mm.

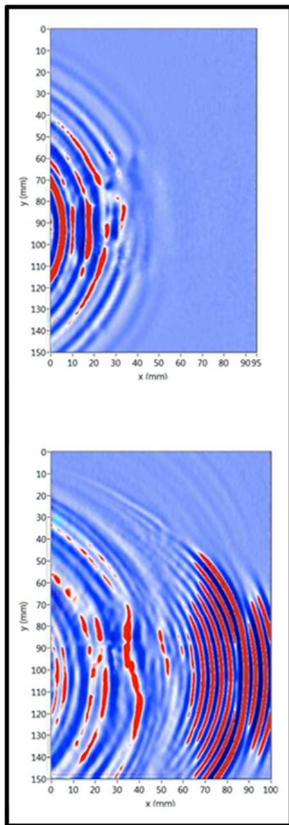


Figure 6. UWPI. Top: no water in the pipe. Bottom: with water

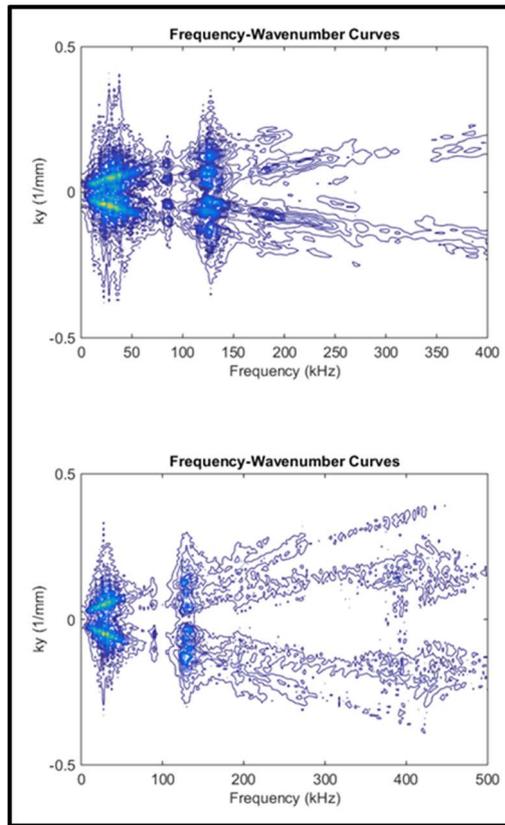


Figure 7. k-f curves. Top: case no water inside the pipe. Bottom: with water

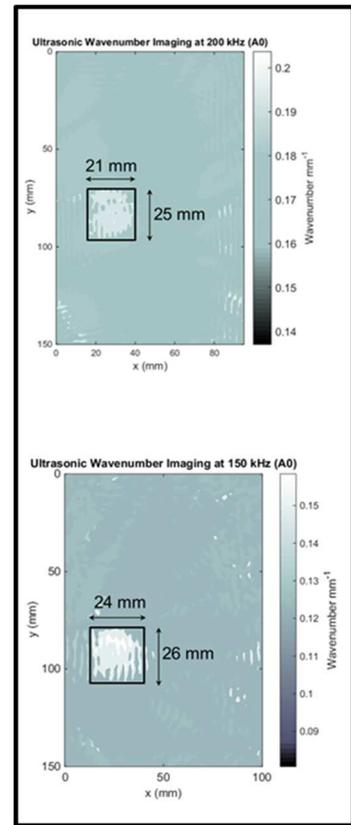


Figure 8. UWI. Top: no water in the pipe. Bottom: with water

4.2. Plastic pipe with slit-type and crack damages

For the case of damage the width of the damages are too small, the UWI algorithm cannot be used as explained in previous section. Figure 9 and 11 show the snap shot of the waves propagation, which indicates the location of the slit damages and the crack damage, respectively. The damage locations were confirmed using the Energy Mapping algorithm as shown in figures 10 and 12.

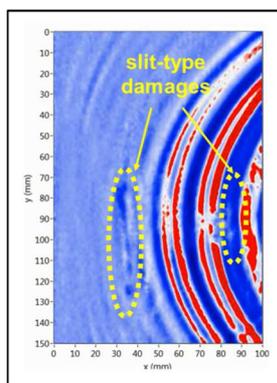


Figure 9. UWPI. Plastic pipe with two slit-type damages

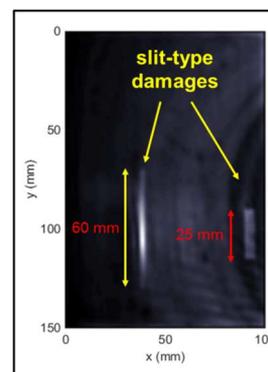


Figure 10. Energy Mapping. Plastic pipe with two slit-type damages

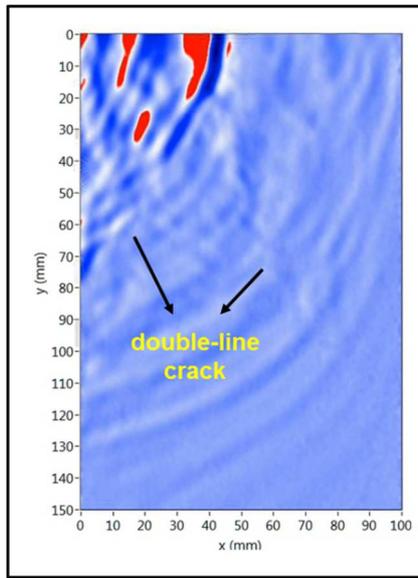


Figure 11. UWPI. Plastic pipe with crack damages

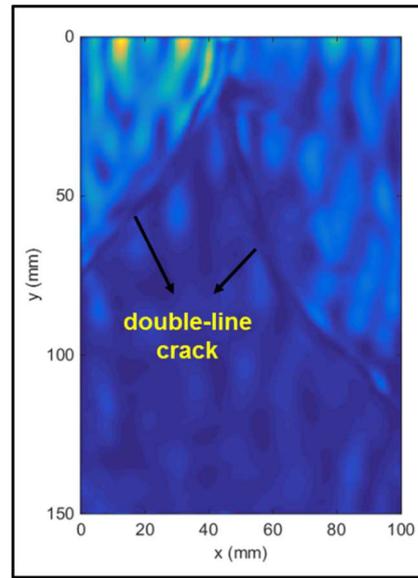


Figure 12. Energy Mapping. Plastic pipe with crack damages

4.3. Composite pipe

The total thickness of this pipe is approximately 7 mm, which potentially make the detection of the damage difficult. However, the actual inspection result in both the UWPI (figure 13) and the waves energy mapping (figure 14) were successfully detected the debonding damage. Also, two small damages were detected at the right side of the debond line (figure 14). This is an unexpected results since these two damages were unnoticed before actual doing the inspection test.

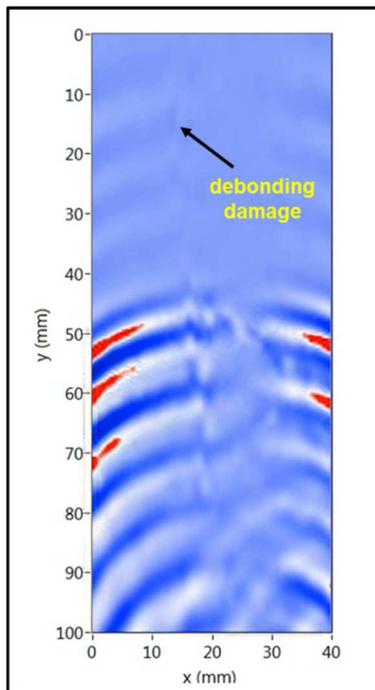


Figure 13. UWPI

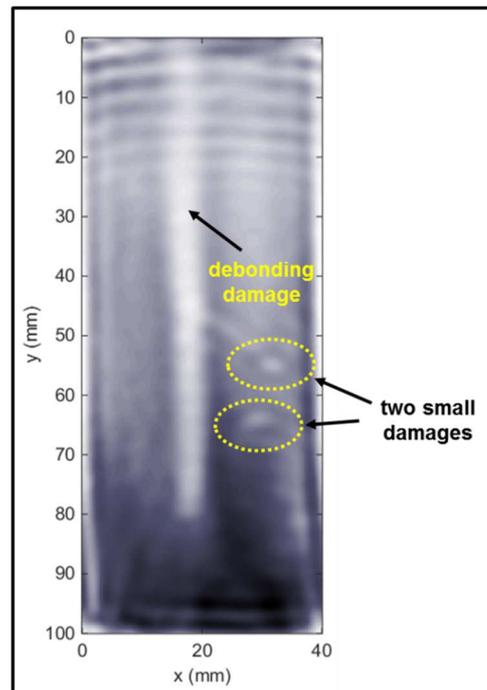


Figure 14. Energy Mapping

4.4. Steel pipe

The large slit-type damage on the left and the weld line were detected using both the UWPI and the energy mapping algorithm. However, the long slit at right side is only found using the energy mapping algorithm. Also, this test poses an interesting problem to the UPI system for future development, which is how to distinguish the damages from the structural features, which is in this case the weld line.

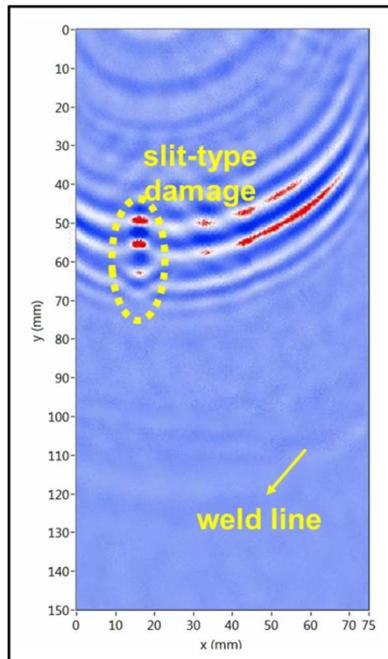


Figure 15. UWPI

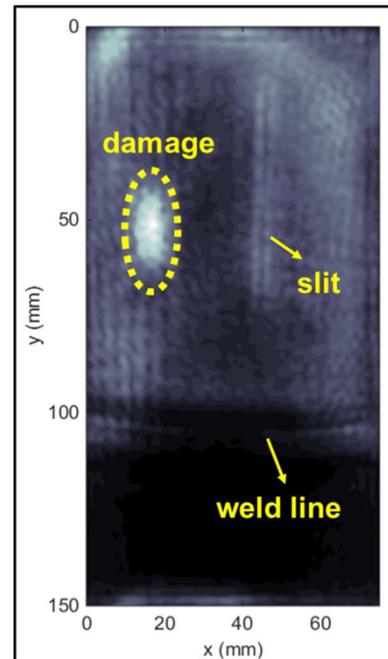


Figure 16. Energy Mapping

4.5. Pipes with a damaged joint

This is the test case where the use of the UWI algorithm shows a superior performance as compare the simple UWPI algorithm. We found that even observing the complete UWPI movie, it is still unable to recognize any significant indication of the damage, whereas the UWI algorithm is able to find quite clearly the area where the damage occurs, which is corresponding to the area with lower stiffness, and as the results: a higher wavenumber of A_0 mode.

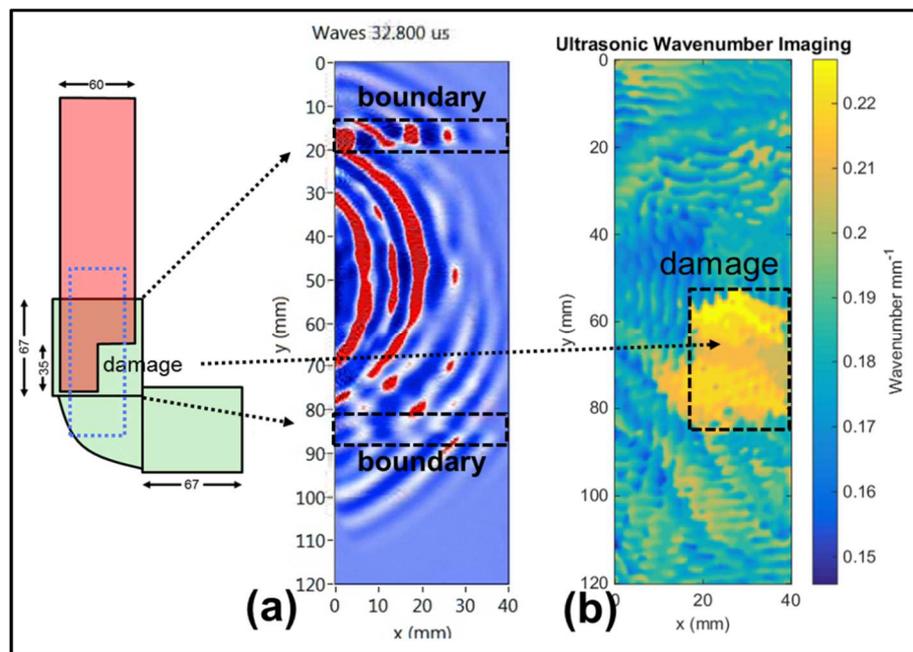


Figure 17. Damage detection of joint damage between two plastic pipes

Conclusions

In this paper, the application of the Ultrasonic Propagation Imager (UPI) for damage inspection of the pipeline were presented. We showed that the UPI can be used effortlessly to detect various types of damages for various types of pipes in different sizes and materials. The developed algorithm has overcome the difficulties posed by the working condition of the pipe structure with water inside the pipe. Those results have proved the feasibility of the UPI system as an effective structural health management system for the real-world pipeline inspection system.

Acknowledgments

This research was supported by the Space Core Technology Development (2013-042548) and Leading Foreign Research Institute Recruitment Program (2011-0030065), through the National Research Foundation of Korea, funded by the Ministry of Science, ICT and Future Planning.

Reference

- [1] Rose J L 2004 *Key. Eng. Mat.* **270-273** 14
- [2] Ostachowicz W, Radzienski M and Kudela P 2014 *Strain*. **50**, 27
- [3] Chong S Y and Lee J R 2014 *Procs. of Advances in Structural Health Management and Composite Structures* (Jeonju, Korea) vol I, p18-1
- [4] Chia C C, Lee J R, Park C Y and Jeong H M 2012 *Opt Laser Technol.* **44** 1507
- [5] Flynn E B, Chong S Y, Jarmer G J and Lee J R 2013 *NDT&E Int* **59** 1
- [6] Lee J R, Cho C M, Park C Y, Shin H J, Jeong H M and Truong T C 2014 *Procs. of Advances in Structural Health Management and Composite Structures* (Jeonju, Korea) vol I, p20-1