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APPLICATION OF DIGITAL ULTRASONIC IMAGE CONSTRUCTION SYSTEM FOR THE DETECTION OF CRACKS IN WATER DISTRIBUTION SYSTEM

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Abstract : A digital ultrasonic image construction system was developed for the nondestructive detection of cracks in water distribution pipes. The system consists of PC based ultrasonic testing system and a scanning device. The PC based ultrasonic system has an ultrasonic pulse/receive board for the generation and reception of ultrasonic signals, an analogue to digital conversion board for the digitization of the received ultrasonic signals, and transducers for the ultrasonic sensors. Using this system, the digitized ultrasonic signals were properly constructed in accordance with the position information obtained by scanning device that moves an ultrasonic transducer along the outer surface of pipes. In the construction of the ultrasonic signals, signal processing concepts, such as spatial average and array concept, were considered to enhance the resolution of ultrasonic images of pipe wall. Using the developed system, crack detection experiments were performed in both laboratory and field, which shows promise for crack detection in the water distribution system.

Key Words : Ultrasonic image construction, Pipe defects, Cracks, Water distribution system.

INTRODUCTION

Water distribution metallic pipes are very important facility in human life in these days. Millions of kilometers of water distribution pipes were constructed and are being constructed. Maintaining the pipeline for the clean water supply is an important task in most industrialized countries. Considering the long history of the pipelines, evaluation of lifetime of pipe and their replacement are of great important. In nuclear, chemical and gas industries, maintenance of piping that contains pressurized and/or hazardous substances has been recognized as a significant task. Therefore, there are many nondestructive methods developed and used for the assessment of the pipes in use. It is difficult to say that water pipes are less important then nuclear pipes in these days. Everyday, more then billions of peoples drink water distributed by pipelines. From this point of view, it is quite urgent to have something that can provide the conditions of water pipes so that one can have data to access pipelines. The easiest way to the assessment of water pipe can be found from the similar cases in other industry that already has experience. Nondestructive testing is the good solutions that can be used for the assessment of metallic pipe in use and without destroy the test structure. And some of the testing methods are reviewed for the physical integrity of water mains.[1,2)]

Among many nondestructive testing methods,

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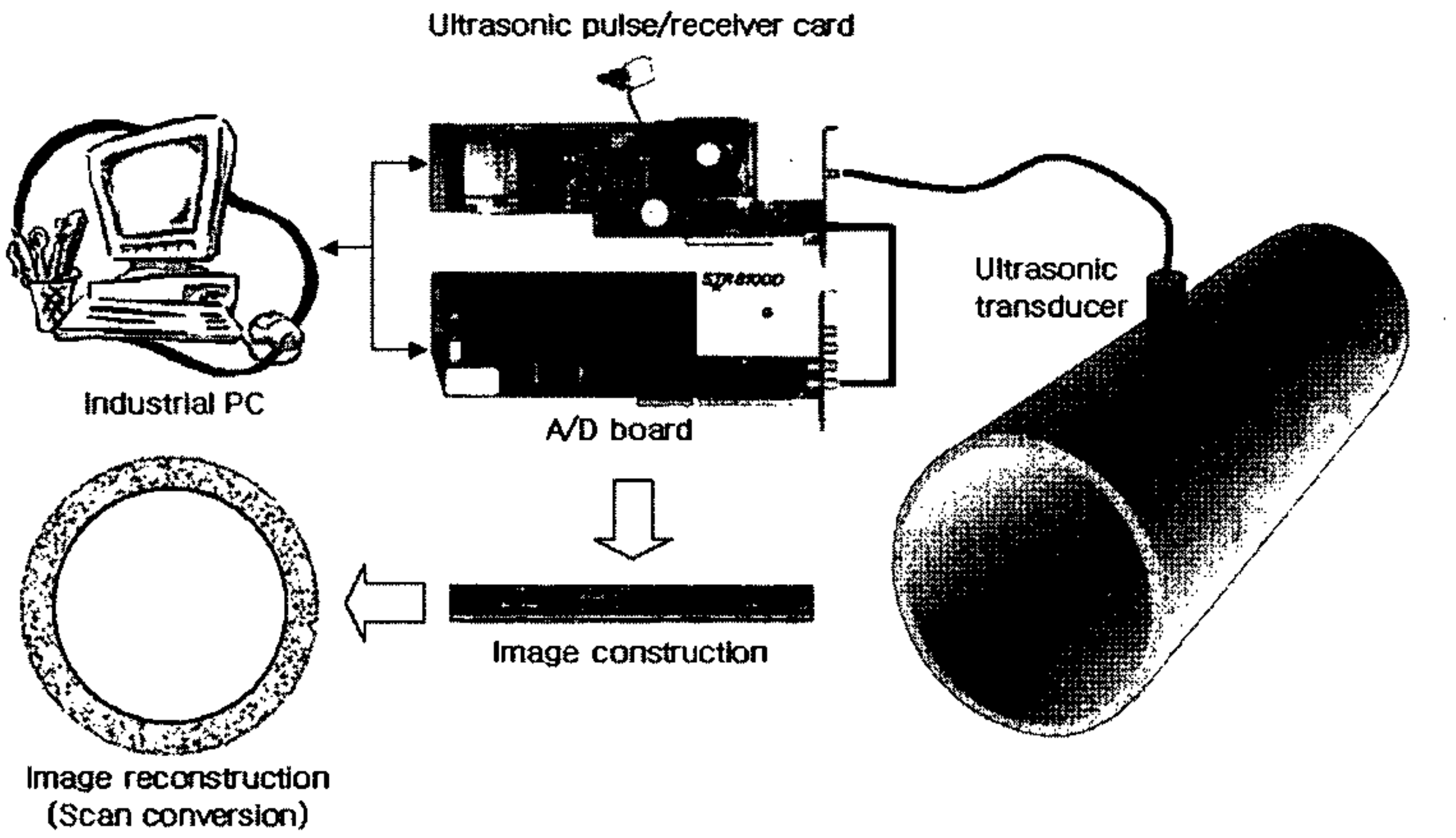


Figure 1. The schematic concept of the ultrasonic nondestructive testing system for water pipe inspection.

ultrasonic testing (UT) and radiography testing (RT) are promising candidates. Radiography testing is used to weld joint inspection at construction field when it is easy to place RT film. As a result of RT, 2D image on RT film is provided. Ultrasonic testing is used for same as RT and provides ultrasonic signals as a result. One can make 2D or 3D images using the UT signals. The industrial trend is going to UT, since UT does not have radiation problems and is fast and effective in many cases. Especially, the UT signals can be stored as digitized electronics files in database systems and further analysis for automated systems. Thus, to assess water distribution pipeline for detecting cracks and corrosions, UT can be the best solution at this moment.[3] Advanced nondestructive testing methods for pipes using ultrasonic guided waves are also under development.[4] Many signal processing methods have been developed for the further analysis of the results.[5-8] This methods can be applied to ECO-DESIGN[9] of pipelines such as rehabilitation, replacement and their maintenance.

In this study, the ultrasonic nondestructive testing system of water piping was developed. Figure 1 shows the schematic concept of the developed inspection system. Ultrasonic pulse/receive card and A/D board are installed in a computer and an ultrasonic transducer scans along the circumference of the outside of the water pipe. The received UT signals are processed to generate 2D images and converted to the final circular forms for the direct mapping to the pipe geometry.

The ultrasonic 2D image represents the cross section of the pipe, which is called as ultrasonic B-scan images. For the improved image quality of the B-scan, received ultrasonic signals are processed to reduce noise and increase defect or back wall echo signals. The main concept to get enhanced resolution is the special superposition of digitized ultrasonic signals received at the different positions with one ultrasonic transducer. It is similar with spatial average in terms of superposition of signals from different positions. In this study, different delay times for both different transducer positions and different image positions are considered in addition to spatial average for the enhanced resolution in the ultrasonic images.

FUNDAMENTALS OF ULTRASONIC TESTING

Fundamental ultrasonic testing method of pipe wall is shown in Figure 2. The excited ultrasonic waves propagate through water layer and hit the outer surface of pipe. Some of the waves are reflected and some are transmitted at the interface. The transmitted waves are also reflected at the back wall of the pipe. The ultrasonic transducer receives both of the reflected waves, since the transducer works as both transmission and reception. Figure 3 shows an example of received ultrasonic signals. The horizontal axis represents the time of flight for the waves and the vertical axis represents the amplitude of the waves. This kind of the representation of the ultrasonic waves is called as A-scan. Because the times of flight of the waves are different according to the length of the path, the echo signals are located at the different location in the time axis. It is necessary to know the velocities of the ultrasonic waves in the water layer and in the pipe wall, and which can be known by the simple test before main experiments. Once one knows the velocities of the waves and the time of flight, it is easy to calculate the distance of the path. Therefore, the difference of the time of flight between interface echo and the back wall echo is used to measure the thickness of the pipe wall. If there are cracks, the ultrasonic waves are reflected and the indications will appear between the interface echo and the back wall echo. If there are corrosions that cause the wall thickness change, the location of the back wall echo will be changed in time axis.

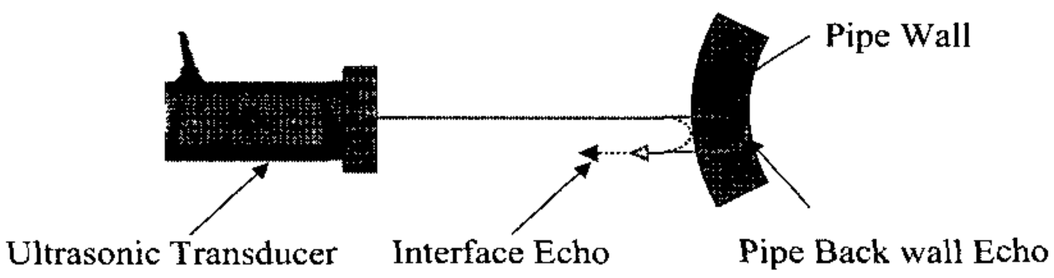


Figure 2. An ultrasonic transducer and ultrasonic waves interaction with pipe.

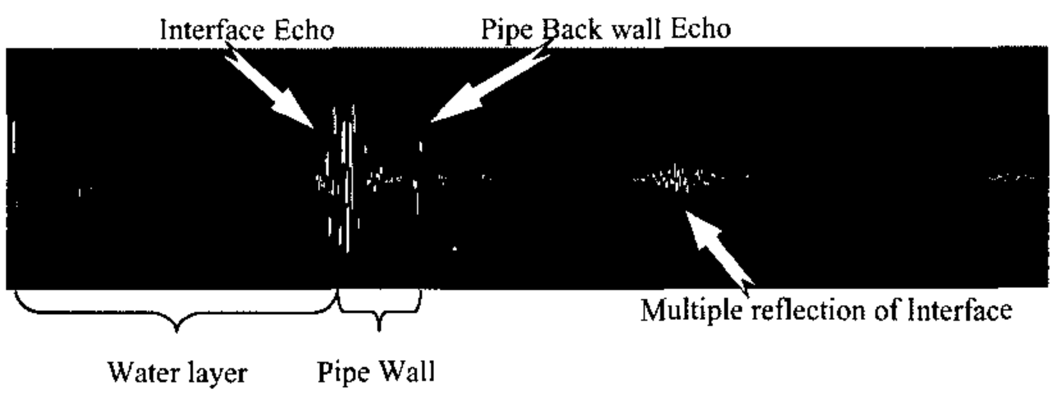


Figure 3. Ultrasonic A-scan signals reflected from a pipe wall shown in Figure 2.

To make ultrasonic images, it is necessary to scan the transducer while A-scan signals are collected and stored in memory. Each A-scan signal should be converted to the line that has brightness level for the amplitude information. Arranging the lines according to the scanning sequence, one can produce the ultrasonic images that have brightness indications for the echo signals. This kind of representation of ultrasonic testing is called as B-scan. Therefore, the B-scan image contains the ultrasonic information of the cross section of the scanned test specimen. And one can easily find the thickness changes and location of cracks with the B-scan images. In the process to make B-scan image, the digitization of the ultrasonic signal is necessary.

DIGITAL SIGNAL PROCESSING

To construct ultrasonic images, B-scan image, it is necessary to scan the transducer along the surface of the test specimen. Figure 4 shows an example of the scanning, in which the transducers are scanned from the position 1 to position 2. Figure 5 shows the signals processing concept for the received ultrasonic signals at two different positions shown in Figure 4. During the scanning process the transducer keeps exciting ultrasonic waves and receiving the echo signals.

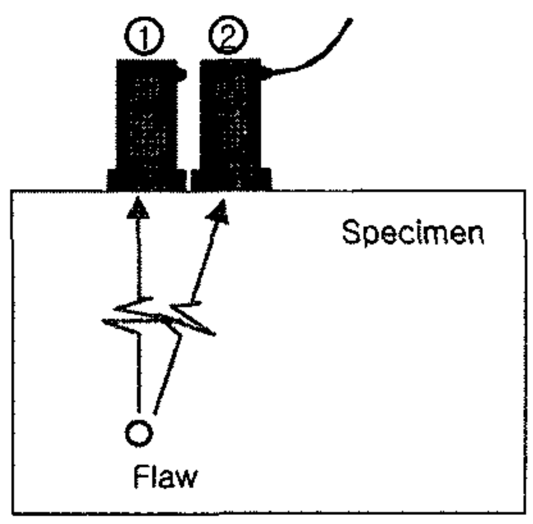


Figure 4. Scanning of ultrasonic transducer and the location of echo source.

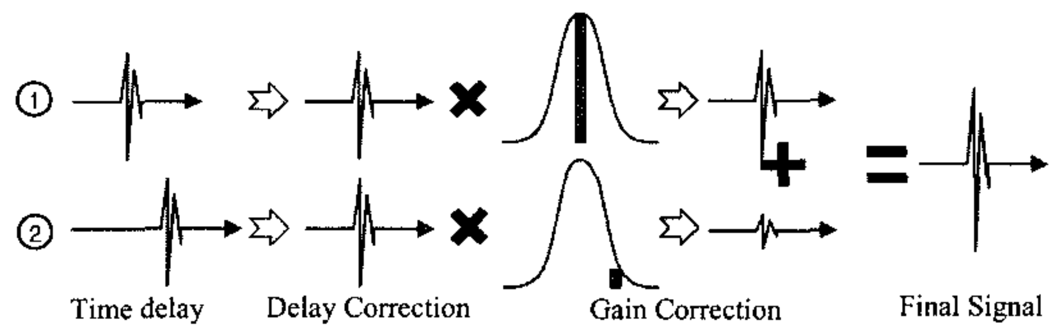


Figure 5. Echo signal correction for the enhanced resolution of ultrasonic testing results.

The received signals are digitized by A/D board and stored in computer memory. As the transducer is scanned along the surface, the relative distance from the echo source such as flaw is changed. This causes the change of the time of flight for the echo, that is, it takes more time to receive the echo signal from the same flaw at position 2 in comparison with position 1. Therefore, there is a certain time delay for signal received at position 2 shown in Figure 5.

In the signal processing, this kind of time delay is corrected through delay correction process, in which the echo signals are in phase and the noise signals are reduced by average effects. The gain correction process shown in Figure 5 can be considered in considering the directivity of the ultrasonic waves and the weighting rate according to the inspection position. The algorithm might be changed with the change of experimental conditions. Basically the gain correction is very useful to optimize the resolution for ultrasonic image quality under the given inspection conditions.

In the calculation of the ultrasonic beam path, it is necessary to consider the curved surface as shown in Figure 6. The algorithm to find the beam path is found using lay theory. In this algorithm, ultrasonic beam path from ($x1$, $y1$) within water layer to ($x3$, $y3$) within pipe wall is considered, where ($x2$, $y2$) is point at the interface, r is the outer radius of the pipe, C_1 is velocity of passing through the medium(water), C_2 is velocity of passing through the specimen(pipe) and the center of the pipe is origin.

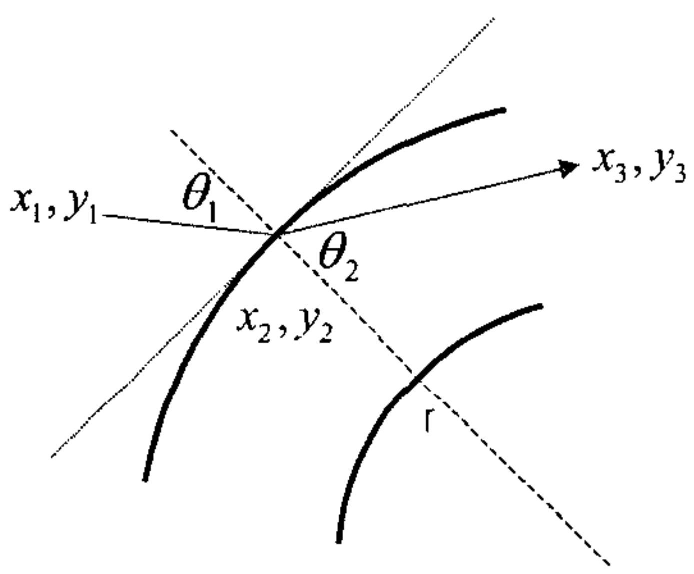


Figure 6. Ultrasonic beam path from ($x1$, $y1$) within water layer to ($x3$, $y3$) within pipe wall, where ($x2$, $y2$) is point at the interface and r is the outer radius of the pipe.

$$\tan\theta_1 = \frac{\sqrt{x_1^2 + y_1^2}\sin\left(\tan^{-1}\left(\frac{y_2}{x_2}\right) - \tan^{-1}\left(\frac{y_1}{x_1}\right)\right)}{\sqrt{x_1^2 + y_1^2}\cos\left(\tan^{-1}\left(\frac{y_2}{x_2}\right) - \tan^{-1}\left(\frac{y_1}{x_1}\right)\right) - r} \quad (1)$$

$$\tan\theta_2 = \frac{\sqrt{x_3^2 + y_3^2}\sin\left(\frac{\pi}{2} - \tan^{-1}\left(\frac{y_3}{x_3}\right) - \frac{x_2}{y_2}\right)}{r - \sqrt{x_3^2 + y_3^2}\cos\left(\frac{\pi}{2} - \tan^{-1}\left(\frac{y_3}{x_3}\right) - \frac{x_2}{y_2}\right)} \quad (2)$$

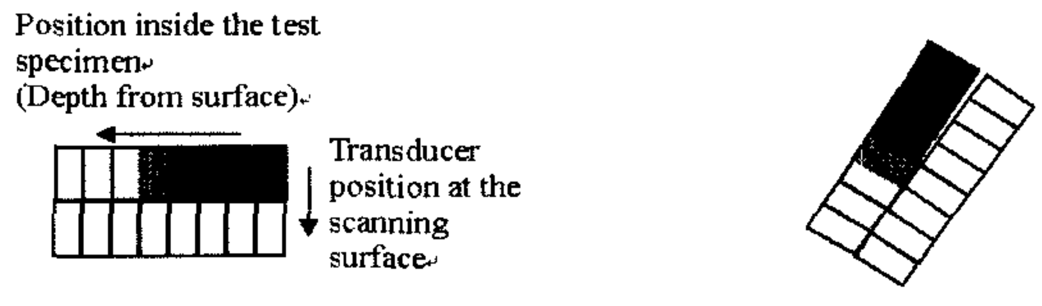
$$\theta_2 = \sin^{-1}\left(\frac{C_2}{C_1}\sin\theta_1\right) \quad (3)$$

$$y_2^2 + x_2^2 = r^2 \quad (4)$$

This algorithm is required when the ultrasonic waves are obliquely incident to the piping surface. Since the velocity of water layer and the piping layer is different, ultrasonic waves are refracted. In the case of the right angle incident of the waves, it is not necessary to consider the refraction, since the waves are traveling same direction. However, it is necessary to consider the velocity difference for both cases.

IMAGE CONSTRUCTION AND SOFTWARE MODULES

B-scan data are stored as a matrix form in which one parameter is the transducer position at the scanning surface and the other is amplitude or brightness level of the ultrasonic signals at the inside position of the test specimen. The common display of B-scan is shown in Figure 7(a). Figure 7(b) shows the scan conversion result of the common B-scan. The scan conversion is performed to represent the B-scan image to circular image, so that the piping geometry can be directly mapped into the ultrasonic image.



(a) (b)

Figure 7. Digitized ultrasonic data represented in (a) common B-scan display and (b) scan conversion of common B-scan for piping.

In the image construction process, smoothing filters, sharpening filters, and edge detection techniques can be selectively used for the optimal images. In doing these image processes, one must be careful to keep all the necessary ultrasonic information. For the quantitative evaluation of the image obtained in this advanced imaging method, it is necessary to have additional study in according to the traditional standard cord. However, in the field of the detection of major cracks and thickness changes in the water pipe field, one may practically use pre-mentioned image processing techniques for the intuitive screening testing.

Figure 8 illustrates the graphic user interface to control ultrasonic testing parameters and to represent A-scan and the ultrasonic images. Actually, development of ultrasonic DIPT(Digital Image Processing Technology)and S/W included several small development tasks of (1) pulser/receiver control module, (2) ultrasonic signal reception program including analogue to digital convertsion, (3) signal processing program including peak value detection, color leveling module, and gate/threshold module, (4) algorithms for cross-section imaging, for color mapping, and for shape mapping, (5) image processing algorithm, and finally (6) graphic user interface (GUI)for the efficient control of the system. In addition to these program modules, a scanner module is developed to have the exact location of the scan position. The scanner module is composed of the encoder and counter signal treatments.

All of these modules are installed into a hand carry field type industrial PC with operating system of Windows 2000 and CPU of Intel Pentium. Ultrasonic pulser/receiver board, analogue/digital conversion board, and counter board are also installed in the PC via ISA slots. Ultrasonic transducers can be connected to the PC via BNC connectors. And a manual scanner or an automated scanner can be connected to PC with proper scanner control software.

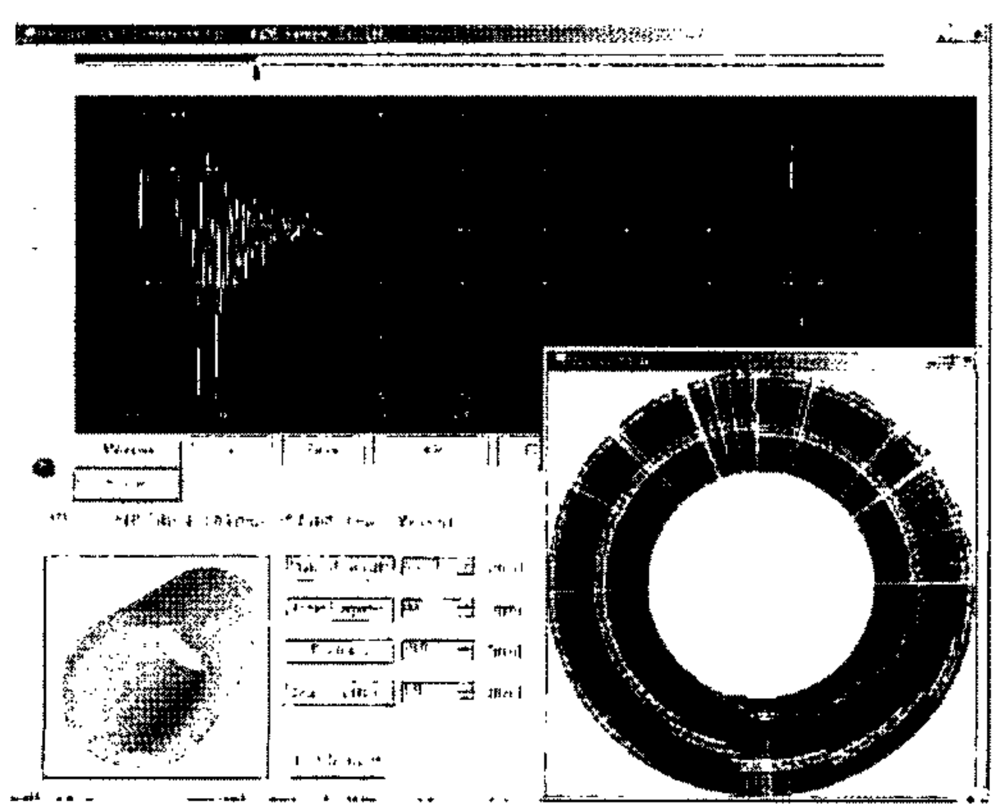


Figure 8. Representation of Ultrasonic Image Construction results by a GUI.

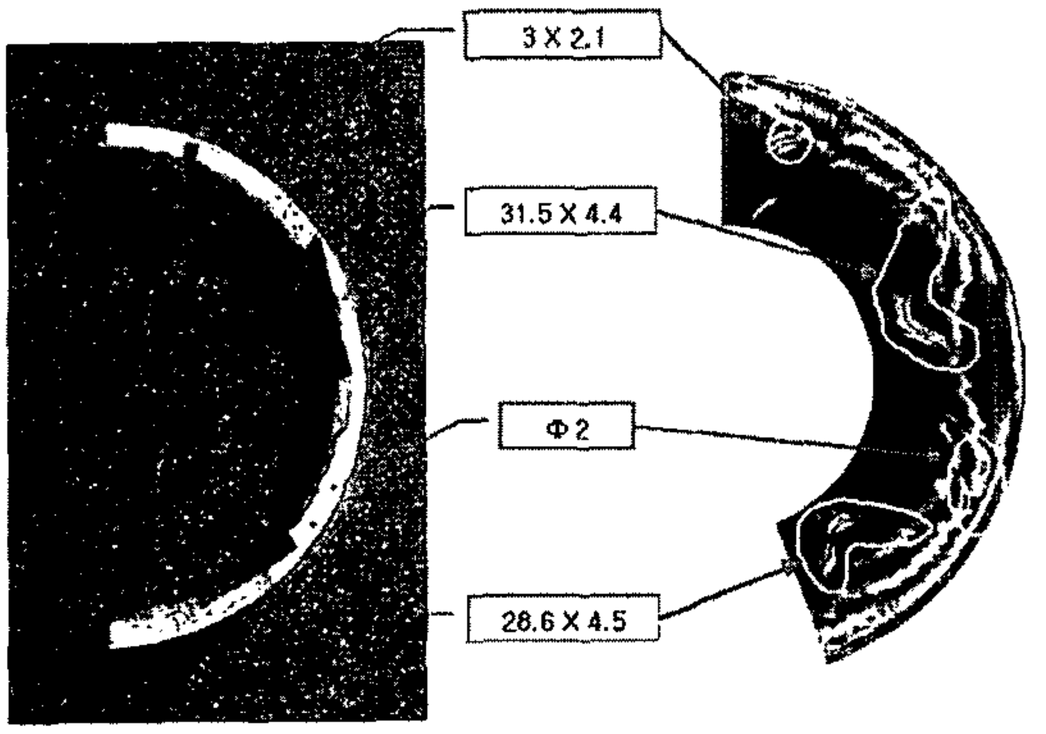
RESULTS

Figure 9(a) shows a used water distribution pipe with artificial defects. Figure 9(b) shows the corresponding ultrasonic image of the cross section of the pipe wall. All of the artificial detects are detected and displayed in the ultrasonic images in which it is easy to locate the defect position. The result confirms that defect and/or wall thinning in water pipe can be detected using the digital ultrasonic image construction system and the developed technology.

Figure 10 shows the detection capability of the defect in inner surface of the plastic coated steel pipes. The pipe is 216 mm in diameter and 5.5 mm in thickness. The width of the defect is 1.5 mm. Depths are 3 mm and 1.5 mm in to steel pipe, and the smallest is only removal of the coated plastic without damage in steel. The ultrasound test indicated the both defects in the steel. The ultrasound dose not indicate the demage of the coating in this setup. To detect the demage of the coating, it is recommended to use a different setup for that.

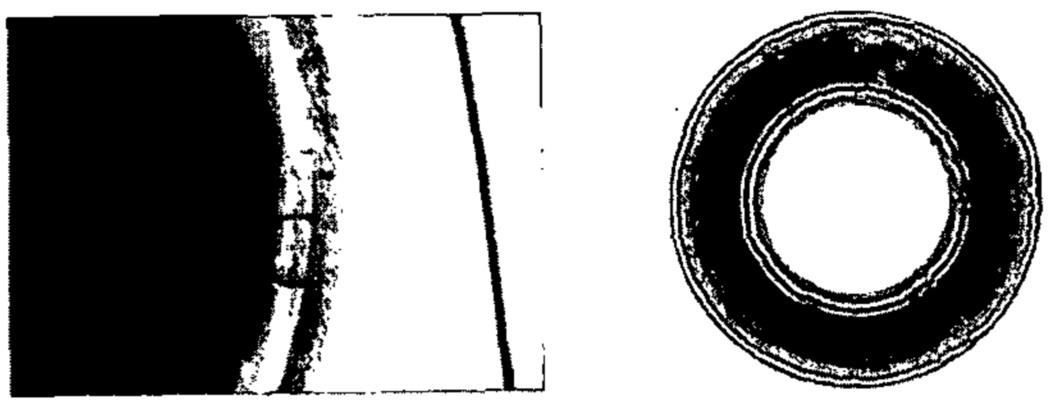
Figure 11 shows the capability of ultrasonic tests to examine the change in the pipe. The test pipe is 167 mm in diameter and the maximum and minimum thickness is 14.4 mm and 10.1 mm respectively. It is intuitive to see the change of the thickness from the ultrasound image.

After the success of the artificial defect detection experiments, the real world application was performed. A water distribution pipe with 700 mm nominal diameter was tested. As shown in Figure 12 (a), the outer surface of the pipe had a layer of corrosion. The rough corrosion layer was removed



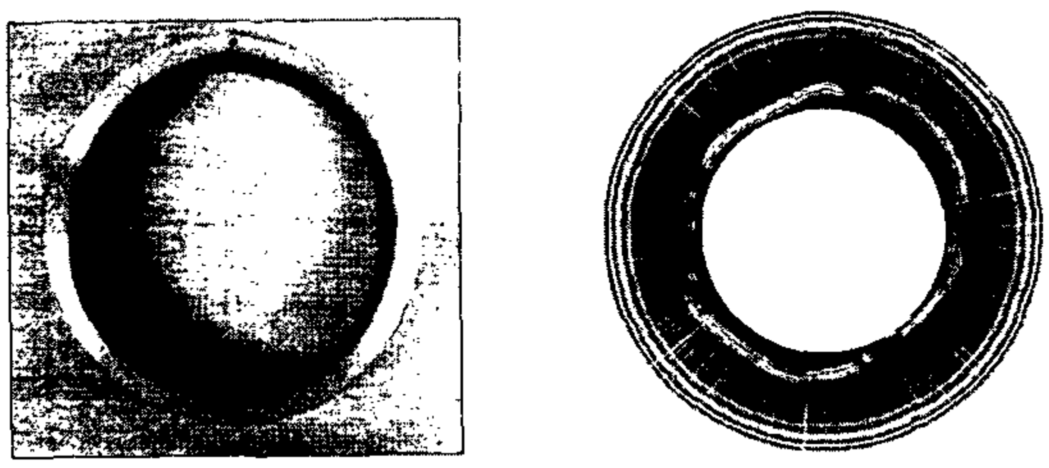
(a) A test specimen [unit: mm] (b) A digital ultrasonic image for the specimen

Figure 9. Ultrasonic nondestructive test results with 10 MHz transducer.



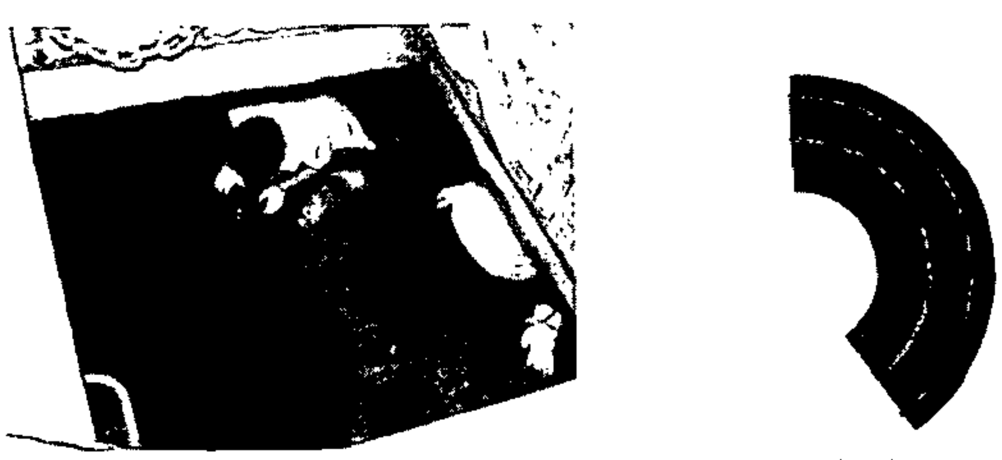
(a) A test specimen (b) A digital ultrasonic image for the specimen

Figure 10. Detection of artificial defects on inner surface of plastic coated water distribution pipe.



(a) A test specimen (b) A digital ultrasonic image for the specimen

Figure 11. Detection of thickness changes of a pipe.



(a) water pipe in service (b) A digital ultrasonic image for the specimen

Figure 12. Ultrasonic test of 700 mm steel water pipe in real world service.

to provide coupling of ultrasound. Basing the result from the ultrasonic image(Figure 12(b)), no serious defect existed in the pipe.

CONCLUDING REMARKS

Ultrasonic nondestructive testing system with digital signal and image processing was developed for the evaluation of water distribution pipes. Digital ultrasonic images are obtained for the cross section of water pipes. Using the algorithm on the delay time controlling superposition for different positions of the transducer and image points, it is possible to enhance the image resolution. Also the enhanced ultrasonic image is converted to the circular form for the direct mapping to the pipe geometry. The developed ultrasonic system and methods can be used for the detection of cracks, corrosions and thickness changes in water metallic pipes.

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