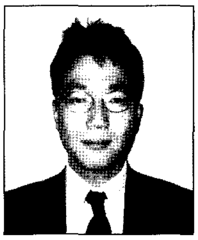
비파괴검사에서 원통유도파의 이용

A Use of Cylindrical Guided Waves for Nondestructive Inspection



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1. INTRODUCTION

Concrete-filled steel pipes have been used as piles for supporting civil and marine structures such as bridges, piers, wharfs, moles, and dolphins. These piles provide good bending resistance, and can be easily spliced for long depth installation. In addition, concrete-filled steel pipes have high strength and ductility, and would lead to an economical solution for bridges since this material costs only 15-20% of the total construction cost of conventional steel bridges. However, poor mortar or concrete filling process into steel pipes causes voids between the filling materials and steel pipes. These voids can accelerate corrosion of steel pipes, which is exposed to corrosion environments such as sea salt and deicing materials. Once the steel pipes are corroded, the most common secondary defect is the delamination at the interface between steel and concrete. Thus, the outside corrosion of the steel pipe reduces the wall thickness of the pipe and the delamination due to internal corrosion of the pipe increases internal volume and pressure. To avoid structural failure due to this type of deterioration, appropriate inspection and repair techniques are to be developed. The inspection predicts which segment of a structure has a problem, and then appropriate repair or rehabilitation of the deteriorated region is carried out. Without precision detection the rehabilitation is expensive and time consuming. That is why we need promising and reliable inspection techniques.

There have been many nondestructive inspection techniques for detecting existing anomalies and deteriorations. It is almost impossible to select one specific technique for a certain application because inspection techniques have their own development stages, advantages, and disadvantages. Choosing one specific technique depends on the type of structure, deterioration, and surrounding environment. However, we may say that acoustic waves techniques are one of the most used nondestructive inspection techniques because of their simplicity and versatility. In addition, since the guided wave technique was introduced, the potential of acoustic waves has increased for inspecting massive structures. That is because guided wave propagates a long distance. Here, we introduce a cylindrical guided wave technique for inspecting the concrete-filled steel pipes. Cylindrical guided waves are guided waves propagating cylindrical structures such as pipes. Experimental results are presented to prove the feasibility of the introduced technique and dispersion curves calculation is conducted to identify the propagated cylindrical guided wave modes.

2. GUIDED WAVES

The acoustic method, including sonic, ultrasonic, and acoustic emission technique uses acoustic properties such as phase velocity, wave attenuation, time history, spectral density, etc. to inspect or monitor the damage of pipes or piles. In general, conventional acoustic methods use reflection, transmission, and scattering of bulk waves. However, such use of bulk waves for pipe or pile inspection is not very economic because of its limitation on the inspection time. In recent years investigators have developed guided wave techniques for inspecting large structures. These techniques have several advantages over the conventional acoustic methods (1) guided waves can propagate a long distance; and (2) there are several wave modes that can have different degrees of sensitivity to different types of defects. However, the described second advantage can be also a disadvantage in the other sense, because the variability of guided wave modes makes problem complicated. In other words, too many wave mode generation bothers wave mode identification. This complication is also related to the dispersive property of guided waves. The acoustic properties such as phase velocity, group velocity, and attenuation, vary with respect to wave frequency or wave number. Thus, wave mode control is another important process for the simplicity of inspection process.

3. EXPERIMENT

To investigate the feasibility of using cylindrical guided waves for detecting the interface delamination between concrete and steel pipe, an experiment is carried and presented here. For this experiment, Electro-Magnetic Acoustic Transducers (EMATs) are used for transmitting, propagating, and receiving cylindrical guided waves. EMATs don't need any couplant; hence, it gives relatively consistent experimental results in comparison to piezoelectric transducers. The experimental setup is shown in Figure 1. Mortar-filled steel pipes with different degrees of separation are inspected. Here, mortar is used instead of concrete because the inner diameter of the steel pipe inspected is too small to inject concrete into the pipe. The use of mortar instead of concrete is not impractical since (1) sometimes in real life mortar is used in pipes; (2) the conclusions derived from the mortar filled pipe tests can be extended to concrete filled larger diameter pipes.

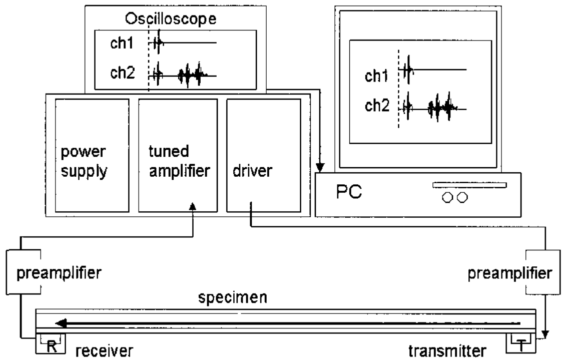


Figure 1. The experimental setup using EMATs (Electro-Magnetic Acoustic Transducers).

Different degrees of separation are artificially fabricated at the interface between steel pipe and mortar i.e. the corrosion-induced delamination is idealized as an already existing separation. This idealization may not exactly represent the real phenomena of the corrosion-induced delamination; however, at least, the separation represents a void that can possibly exist in the steel pipe. This void is usually made when the pipe is not very well grouted by mortar or concrete. Figure 2 describes the geometries of the inspected specimens. These five specimens include different length of separation, respectively. Next, time history curves are obtained and the degrees of separations are related to the change in the time history curves. After the degree of separation and time history curves are correlated, the degree of separation can be predicted or quantified from the change in the time history curves. An analytical study is also conducted to identify wave modes appeared in the time history curves. These wave modes are plotted on group velocity dispersion curves to complete the identification process.

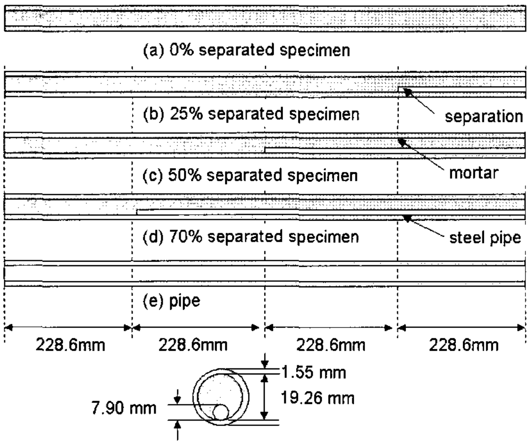
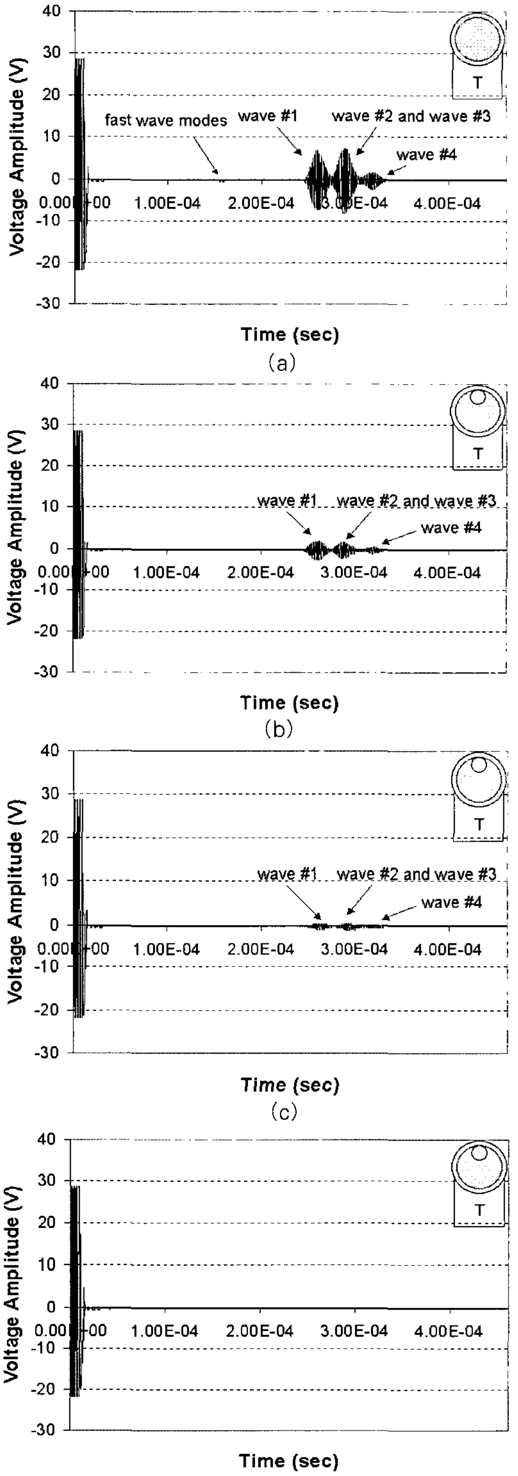


Figure 2. Geometries of five different specimens: (a) no void or 0% void, (b) void length is 25%, (c) void length is 50%, (d) void length is 75%, and (e) hollow steel pipe.

4. OBSERVATION

Figure 3 is the experimental results showing time history curves of the different specimens. The first step of analyzing the experiment results is identifying received waves. In Figure 3, there are three wave packets in each figure. These wave packets can be different wave modes or some of those can be same wave mode reflected from the pipe ends. To identify these wave packets, we moved the transmitter-receiver positions, then we found only the first wave packet represents a wave mode and other wave packets are the same mode reflected from the pipe ends (Na and Kundu, 2002). So, we name the first wave packet as wave #1 and others are wave #2, #3, and #4, respectively as shown in Figure 3. From these tests, it is concluded that longer voids significantly reduce the received signal amplitude; hence, the degree of void or separation can be predicted from the received signal amplitude. Then, the steel pipe without internal mortar was tested. Amplitudes of the time history curves for the pipe without mortar are much larger (see Figure 4); hence, the mortar inside reduces the signal strength.



(a)

(b)

(c)

(d)

Figure 3. Time history curves of (a) void free, (b) 25% void length, (c) 50% void length, and (d) 75% void length specimens. The voids are located in the top part of the specimen cross-section as shown.

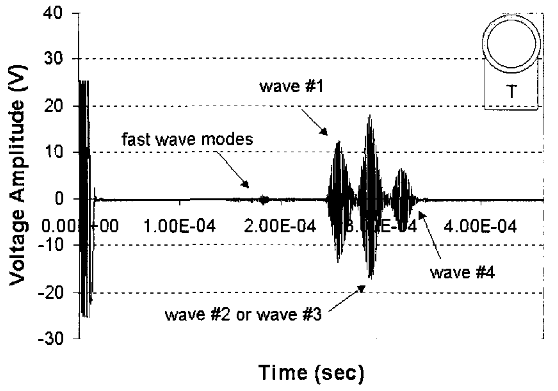


Figure 4. Time history curves of the hollow steel pipe.

5. MODE IDENTIFICATION

An interesting observation from the experimental results is that the wave packet positions of mortar-filled steel pipes and hollow pipes are identical. Hence, in the frequency range of our interest one can use the group velocity dispersion curves of the hollow steel pipe to identify the wave modes of both hollow and concrete-filled steel pipes. This gives computation efficiency because for the hollow pipe analysis we need just one type of boundary condition: solid-vacuum at the outer and inner walls and it avoids all standing wave modes generated in the mortar for the mortar filled pipe. Computation of all standing wave modes in mortar takes more computational time and those modes are not detected in our experimental results anyway. The material properties of the steel pipe used for calculating the wave group velocity versus frequency curves, also known as dispersion curves, are (a) density = 7932 kg/m3, (b) longitudinal wave speed = 5960m /sec, and (c) shear wave speed = 3260m/sec. These material properties are obtained from the handbook (Pavlakovic and Lowe, 2000). From the material properties one can also obtain phase velocity dispersion curves. Phase velocity of a guided wave describes the rate at which individual crests of the wave move while group velocity of a guided wave displays the rate at which the wave packet travels.

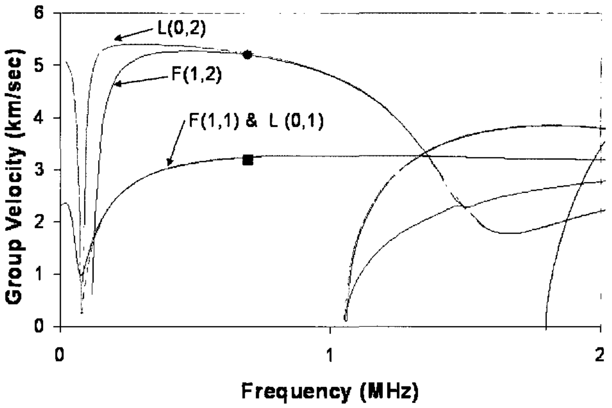


Figure 5. Group velocity dispersion curves of the steel pipe. Material properties are given in the text. The solid square corresponds to F(1,1) and L(0,1) mode and the solid circle corresponds to the L(0,2) mode. Here, F(1,1) and L(0,1) are identical in the frequency range of interest.

Figure 5 shows the group velocity dispersion curves of the steel pipe. The solid square on the group velocity dispersion curves corresponds to the group velocity computed from the wave #1 of Figure 4. The group velocity is obtained by dividing the distance between the transmitter and the receiver by the time of travel. The central time of the first wave packet is used for the time of travel. This group velocity comes out to be 3.193 km/sec, and the signal frequency is 0.694MHz. This point matches with the F(1,1) and L(0,1) mode, they overlap over the most frequency range. Here, F and L represent flexural and longitudinal wave modes, respectively. The first numerical index indicates the integer number of wavelengths around the circumference of the cylinder (or the theta-dependence) and the second index indicates a counter variable. Since longitudinal wave modes are axially symmetric the first index is always zero for L-modes.

In the group velocity dispersion curves (Figure 5) there are other modes in addition to the F(1,1) and L(0,1) modes at 0.694MHz frequency. These are F(1,2) and L(0,2) modes that are faster than F(1,1) and L(0,1). Where are these wave modes in the time history curves of Figure 4? A closer look of Figure 4 shows a weak wave in front of wave #1. To investigate these waves we enlarged this region and presented it in Figure 6. One can see several wave packets in Figure 6. The time corresponding to the peak of the first wave packet is 158.6sec and hence, the group velocity is 5.198 km/sec. We plot this group velocity point (frequency = 0.694 MHz, group velocity = 5.198 km/sec) on the group velocity dispersion curves by using a solid circle (see Figure 5). This solid circle can correspond to L(0,2) or F(1,2) mode; however, the logical conclusion is that it is L(0,2) mode since this mode is the fastest mode. Other wave packets arriving right after the L(0,2) mode correspond to the F(1,2) mode as well as these two modes after being reflected at the pipe boundires. Since the group velocities of these two modes, L(0,2) and F(1,2) are almost identical it is difficult to distinguish between these two modes. We can also see that these fast modes appear in Figures 3a although their amplitudes are very small.

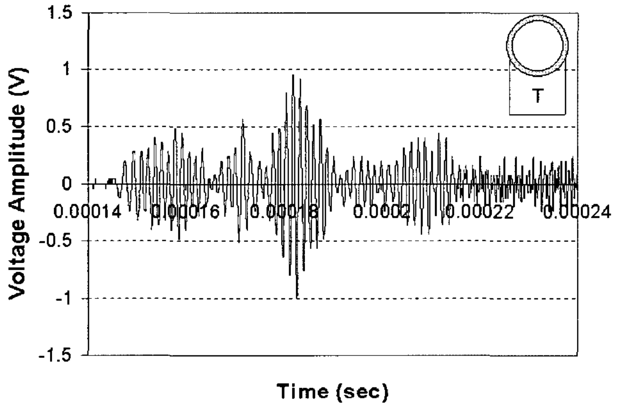


Figure 6. Time history curves of the fast wave modes shown in Figure 4. This time history plot shows direct arrivals of L(0,2) and F(1,2) modes and arrivals of the same modes after being reflected at the pipe boundaries.

6. CONCLUSION

Cylindrical guided waves were used here for internal void inspection of concrete-filled steel pipes. EMATs (Electro-Magnetic Acoustic Transducers) are used as both transmitter and receiver for generating and receiving the cylindrical guided waves. Time history curves are experimentally obtained and then these curves are studied for different degrees of interface separation or voids of different lengths. It is shown that the received wave amplitudes are dependent on void lengths. Different wave modes were recorded in the time history curves and identified on the group velocity dispersion curves. This study shows that the EMAT-based cylindrical guided wave techniques are very effective for the void detection and estimating their lengths in concrete-filled steel pipes.

ACKNOWLEDGEMENT

This article is a modified version of the paper "EMAT-Based Inspection of Concrete-Filled Steel Pipes for Internal Voids and Inclusions" published in Journal of Pressure Vessel Technology. A typing mistake in the paper is corrected here. If you need more detailed experiment and mode identification procedures, please see the reference.

REFERENCE

1. Na, W.-B. and Kundu, T. EMAT-Based Inspection of Concrete-Filled Steel Pipes for Internal Voids and Inclusions, *Journal of Pressure Vessel Technology - Transactions of the ASME,* Vol. 124, 2002, pp 265-272
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