CIRCUMFERENTIAL GUIDED WAVES FOR DEFECT DETECTION IN COATED PIPE

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ABSTRACT. Circumferential guided wave propagation behavior in a viscoelastic multi-layered hollow cylinder is studied to provide a baseline for defect detection in tar coated pipelines. Theoretical work was carried out by developing the appropriate dispersion curves and wave structures for circumferential guided waves in a pipe coated with a viscoelastic material. Parameters that affect wave attenuation were investigated with some initial guidelines being established for improved penetration power. Low frequencies are suggested from both attenuation and detection depth points of view. Under this guidance, experiments utilizing a linear transducer array were conducted at a low frequency for successfully detecting delamination and volumetric defects in tar coated pipe. A study was carried out to find the appropriate features for defect detection in coated pipe and a test protocol based on this study is recommended and summarized.

KEYWORDS: circumferential guided wave, multilayered structure, viscoelastic coating, defect detection, ultrasonics, pipe
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INTRODUCTION

Pipelines are used in almost every industry that has a need to provide a large scale distribution of their product, be it gas, oil, water, etc. The electrical utility industry uses pipes as conduits for the distribution of electricity, with especially complicated configurations, such as the trifurcation joints, used in inner city manholes. These pipelines are both above ground and below ground and are thus exposed to a variety of changing environmental conditions that can lead to corrosion and/or coating separation at the outer diameter of the pipes. Therefore, viscoelastic coating (coal tar, epoxy) is widely used in the pipeline industry for corrosion protection. Defective pipelines can cause fatal failures, property damage, and high litigation and replacement costs. An effective NDE method is needed to provide useful information to the pipeline industry as corrosion and delamination detection is critical for purposes of maintenance and repair.

Since the middle of the 1980's, ultrasonic guided wave techniques have been developed and applied rapidly in the field of NDT because of their long-range testing ability and efficiency compared with the traditional point-by-point bulk wave methods [1]. Presented

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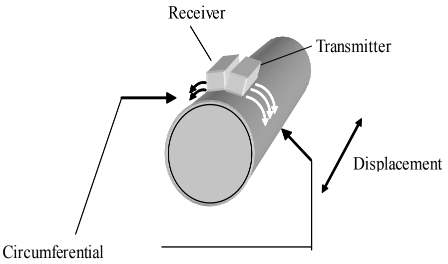


FIGURE 1. The use of circumferential guided waves to find pipe defects under tar tape coated pipes.

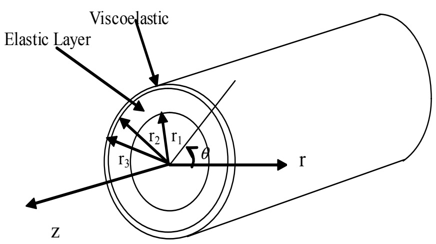


FIGURE 2. Cylindrical coordinates of a hollow viscoelastic coated cylinder and dimensions.

in this paper is the development of an ultrasonic circumferential guided wave technique, which exhibits the ability to detect defects [2-3]. Figure 1 portrays the concept of circumferential guided waves for this application. The difficulty of defect inspection in a coated pipe usually comes from the attenuation and wave energy distribution change along the pipe wall due to the existence of coating, which may reduce the inspection capability significantly. Therefore, theoretical work was carried out first by developing the dispersion curves and wave structures in a pipe with viscoelastic coating. The goal was to find an appropriate frequency with less attenuation and an appropriate energy distribution. Based on the recommendation from theoretical results, a piezoelectric linear transducer array generating SH circumferential guided waves at a low frequency range is designed to provide the best results in terms of defect detection and sizing. Experiments on a coated pipe with a simulated defect were conducted and a preliminary featured-based decision (defect, no defect) model was then constructed.

DISPERSION CURVES

For a pipe with a viscoelastic coating, the phase velocity dispersion curve, attenuation dispersion curve and wave structure were calculated using the global matrix technique. Figure 2 shows a viscoelastic coated pipe. According to the correspondence principle [4], under a steady state, time harmonic assumption, the guided wave propagation solution for an *N*-layered pipe with one or more viscoelastic layers can be acquired simply by substituting the elastic modulus of the respective layers with the complex viscoelastic modulus into the dispersion equation for a totally elastic *N*-layered pipe. The dispersion equation of an *N*-layered viscoelastic pipe can be generated similarly by just using the complex viscoelastic constants instead of the elastic constants.

The displacement u_z^n of circumferential SH wave in the nth layer can then be expressed as in equation (1):

$$u_z^n == \frac{ik^n}{r_{n+1}}\left[C_1^n J_{\hat{k}^n}(k^n r) + C_2^n Y_{\hat{k}^n}(k^n r)\right] e^{i(k^n r_{n+1}\theta - \omega t)}, \qquad r_n \le r \le r_{n+1} \tag{1}$$

The stress can be calculated by equation (2):

$$\sigma_{rz}^n = \mu^n \frac{i(k^n)^2}{2r_{n+1}}\left[C_1^n (J_{\hat{k}^n-1}(k^n r) - J_{\hat{k}^n+1}(k^n r)) + C_2^n (Y_{\hat{k}^n-1}(k^n r) - Y_{\hat{k}^n+1}(k^n r))\right] e^{i(k^n r_{n+1}\theta - \omega t)} \tag{2}$$

where k is wave number and $\hat{k}$ is a wave number related parameter, J and Y represent Bessel functions, C represents unknowns, and μ^n is a Lamé's constant. See [5] for more details about the wave theory and nomenclature.

Boundary conditions are 2 traction-free conditions at the inner and outer surface and 2(*N*-1) displacement and stress continuity conditions at the (*N*-1) interfaces:

$$\sigma_{rz}\big|_{r=r_1, r_{N+1}} = 0; \quad \begin{Bmatrix} u_z \\ \sigma_{rz} \end{Bmatrix}_{\substack{Layer=n \\ r=r_{n+1}}} - \begin{Bmatrix} u_z \\ \sigma_{rz} \end{Bmatrix}_{\substack{Layer=n+1 \\ r=r_{n+1}}} = 0, \quad n=1,2,...,N-1 \tag{3}$$

There is a total of $2N$ boundary conditions. Each layer has two unknowns C_1^n and C_2^n, and thus there is a total of $2N$ unknowns. The layer matrix is expressed in equation (4):

$$\begin{Bmatrix} u_z \\ \sigma_{rz} \end{Bmatrix}_{Layer=n} = [A^n] \begin{Bmatrix} C_1^n \\ C_2^n \end{Bmatrix} e^{i(k^n r_{n+1}\theta - \omega t)} \tag{4}$$

The $2N \times 2N$ global matrix can be constructed after applying the $2N$ boundary conditions and the dispersion equation of the N-layered pipe can be expressed as (5):

$$|A|_{2N\times 2N} = 0 \tag{5}$$

For a multi-layer pipe with viscoelastic layers, complex viscoelastic constants are then substituted into equation (5), in place of the elastic ones. Complex root searching can be carried out in a 3-dimensional space (frequency, real part of k^*, and imaginary part of k^*) [6]. The eigenvalues of the system are then used to construct the dispersion curves and the eigenvectors are used to construct wave structures. The wave number root k^* becomes a complex number. The complex root is composed of the real part Re(k^*), which results in the phase velocity dispersion curve, and the imaginary part Im(k^*) leads to the attenuation constant as well as the attenuation dispersion curve:

$$c_p(\omega) = \frac{\omega}{\mathrm{Re}(k^*)} = \frac{1}{\mathrm{Re}(1/c^*)}; \quad \alpha(\omega) = \mathrm{Im}(k^*) = \frac{\omega}{\mathrm{Im}(1/c^*)} \tag{6}$$

The calculated attenuation dispersion curves for a 10 inch schedule 40 pipe coated with bitumen tape are shown in Figure 3, where the attenuation increased with the frequency and the layer thickness. It can be seen that the frequency range from 20 kHz to 40 kHz provides reasonably low attenuation. A wave structure analysis was carried out in order to tell the inspection potential at different wall depths. The results show that the percent energy carried by the elastic layer becomes less as the frequency and coating thickness increase. Therefore, it would be safer to use lower frequency in order to realize a more reliable detection.

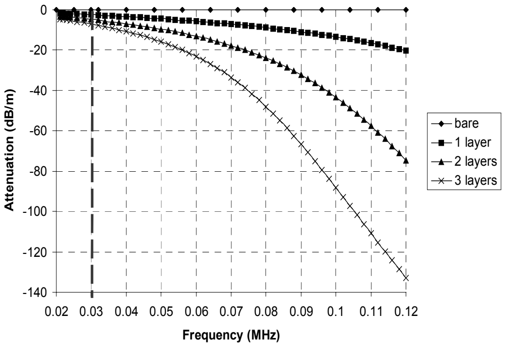


FIGURE 3. Calculated attenuation dispersion curves of n0 circumferential SH wave in a steel pipe (10 inch schedule 40) with different coating conditions (the thickness of each layer is 1 mm), showing wave attenuation increases significantly as frequency and/or coating thickness increase.

EXPERIMENTAL STUDY

For circumferential guided wave inspection as shown in Figure 1, the inspected area was limited to the axial size of the transducers used. To overcome this limitation, a 26” long linear array with 6 channels and 24 transducers was designed as seen in Figure 4. The benefit of using a linear array is that beam spreading can be effectively reduced, especially for the middle two channels, thus realizing consistent inspection ability.

Experiments were carried out on a 10’’ schedule 40 pipe coated with tar tape as shown in Figure 5(a). Frequency sweeping was first carried out in the 20 to 40 kHz range suggested by previous theoretical studies, with the best frequency found to be 30 kHz from signal width and SNR points of view. A typical wave signal at 30 KHz is shown in Figure 5(b), where wrap around signals attenuate gradually with circumferential wave propagation distance. Two key features were identified: The attenuation factor of the wave train produced by the periodic traversal of the input pulse around the circumference of a pipe and the appearance of an echo between the periodic pulse pattern.

The amplitude $A(x,\omega)$ of a propagating wave signal is a function of frequency and the wave propagation distance:

$$A(x,\omega) \approx e^{-\alpha(\omega)x} \tag{7}$$

where $\alpha(\omega)$ is the attenuation constant and x is the wave propagation distance. The attenuation constant, $\alpha(\omega)$ can be expressed in equation (8):

$$\alpha(\omega) = -\frac{1}{x_1 - x_2}\ln\left(\frac{A_1(x_1,\omega)}{A_2(x_2,\omega)}\right) \tag{8}$$

where A_1 and A_2 represent the amplitudes of two signals propagating with distance x_1 and x_2 respectively.

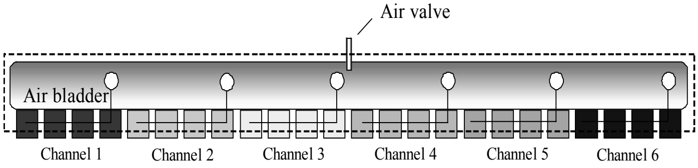
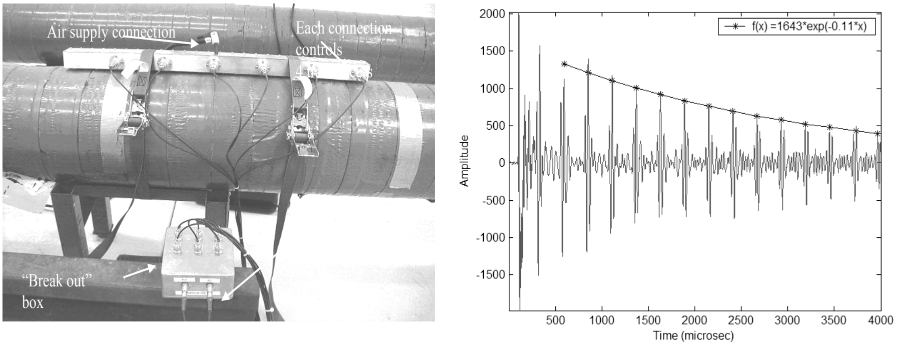


FIGURE 4. Linear transducer array: Coupling is enhanced by the use of an air bladder which applies pressure to the transducers and pushes them into the coating. (Pressure ~ 30 psi).



(a) (b)

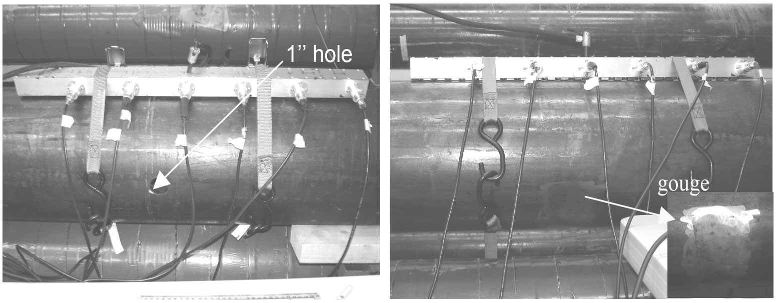
FIGURE 5. (a) Experiment set up and (b) sample signal of 30 KHz circumferential SH wave, with an exponential curve fitting to the wrap around signal peaks which gives the attenuation factor.

Attenuation of the wrap around signals could be an excellent feature for defect detection in addition to the direct defect reflection echoes and wrap around wave amplitudes. The linear array transducer used in this experiment was dry coupled by applying sufficient pressure on it, resulting in signal amplitude changes due to the air bladder pressure variations. However, the benefit of using the attenuation constant feature is that it is consistent under different coupling pressures. This was proved by the experimental study. Two experiments were performed in the pulse-echo mode. One was a hole drilling experiment and the other was a delamination/gouge detection experiment.

Hole Detection Experiment

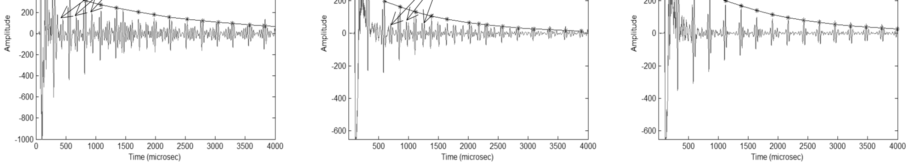
Experiments on a 1'' hole were carried out as shown in Figure 6(a) where the array is about 90° away from the hole. The signal in channel 3 is shown in Figure 7. Apparent reflected echoes from the hole could be found between two wrap around echoes for channel 3. Comparing Figure 7(a) and (b), it can be found that one-ply coating reduces signal amplitudes but not inspection capability. Because the hole is physically one quarter of the circumference away from the array, the reflected wave was right in the middle of the two wrap around waves, indicating a wave propagation distance of a half circumference. The result in Figure 7(c) shows a testing blind area when the hole is 180° away from array.

The attenuation constants were summarized for all 6 channels in Figure 8 considering with/without coating and with/without hole. Compared with the no-defect case, the attenuation constants for the with-hole case do not increase much, which means that small defects such as a 1'' hole cannot contribute a large effect on signal attenuation.



(a) (b)

FIGURE 6. Detection experiments of (a) a 1" hole and (b) gouge in a 10" schedule 40 pipe, using 30 KHz circumferential SH waves generated by a linear array transducer.



(a) no tar coating, hole about 90° away from array

(b) with one-ply tar coating, hole 90° away from array

(c) with one-ply tar coating, hole 180° away from array

FIGURE 7. 30KHz circumferential SH wave signal for Channel 3, showing the hole has strong intermediate reflection echoes.

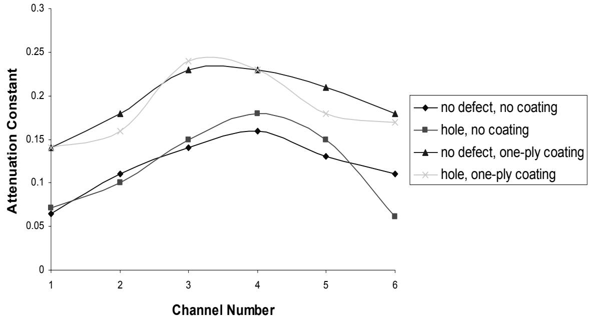
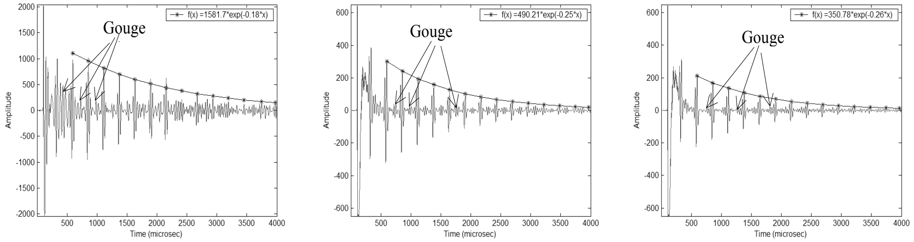


FIGURE 8. Attenuation constants at channel 1-6 for 30 KHz SH wave in a 10'' schedule 40 pipe with a 1'' hole 90° away from array. Note the existence of small hole does not introduce apparent attenuation.

Gouge Detection Experiments

As with the hole detection, experiments on the gouge as shown in Figure 6(b) were also done. For coated pipe, a Teflon tape insert was used to simulate a delamination between the gouge and the tar coating. In this study, the gouge/insert was moved over different distances from the transducer array position in order to find the appropriate inspection technique.

First, the array was placed 10'' away (about 106°) from the gouge's top edge. The results are shown in Figure 9(a) and (b) for no tar coating and tar coating respectively. Gouge echoes can be seen for both cases, although the echoes are not as apparent as those from the through hole shown before. This is because the through hole has a sharp edge which easily results in wave reflections. However, for the gouge, the edge is not so sharp and regular, thus leading to lower reflection amplitudes. The second array position was about 6'' away from the gouge with results shown in Figure 9(c). This time the echoes are closer to the wrap around signals and partially superimposed with them. This is caused by the wide pulse width for the 30 KHz frequency, which generates a certain inspection blind area. To overcome this shortcoming, changing array positions is a solution. Attenuation constants for the 6 channels in Figure 9(a) and (b) are summarized in Figure 10 and compared with the two previous no-defect results, with/without coatings. It can be observed from the figure that the attenuation constants mostly increase in such a sequence: 1. no defect without coating; 2. gouge/insert 10'' away from transducer without coating; 3. no defect with one-ply coating; 4. gouge/insert 10'' away from transducer with one-ply coating.



(a) no tar coating, gouge top edge about 10'' (106°) away from array

(b) one-ply tar coating with Teflon insert, gouge top edge about 10'' away from array

(c) one-ply tar coating with Teflon insert, gouge top edge about 6'' away from array → blind inspection area

FIGURE 9. 30 kHz circumferential SH wave signal of Channel 3 for the experiment on gouge.

The third array position was 180° away from the gouge by putting the array on top and the gouge on the bottom. As predicted, no defect echoes were found for both cases with/without coating. Observation of the attenuation constants is similar with that in Figure 10. These observations could give enlightenment on how to use the attenuation constant feature. If there are no reflected defect echoes but obvious higher attenuation constants are found, the transducer position could be changed by a certain number of degrees to inspect the blind area, which is wide for low frequency.

A test protocol based on this study is recommended and summarized in a flow chart as shown in Figure 11. Two linear arrays are suggested, or the repositioning of one, to acquire data. If intermediate echoes are found, a delamination or other defect exists. If not found, attenuation constants will be used as another feature to tell whether there are no defects or the coating is too thick to tell. Note that the protocol is based on a hypothesis that this method works if delamination is followed by corrosion. Generally we will not see a subtle delamination.

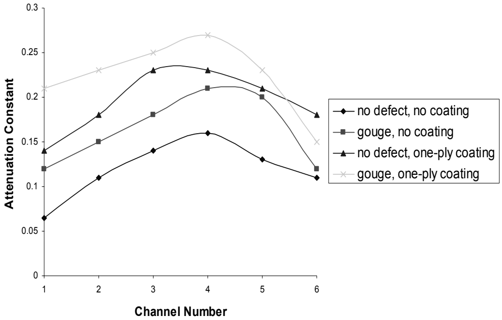


FIGURE 10. Attenuation constants at channel 1-6 for 30 KHz SH wave in a 10’’ schedule 40 pipe for four cases: no defect without coating; gouge/insert 10’’ away from transducer without coating; no defect with one ply coating; gouge/insert 10’’ away from transducer with one ply coating.

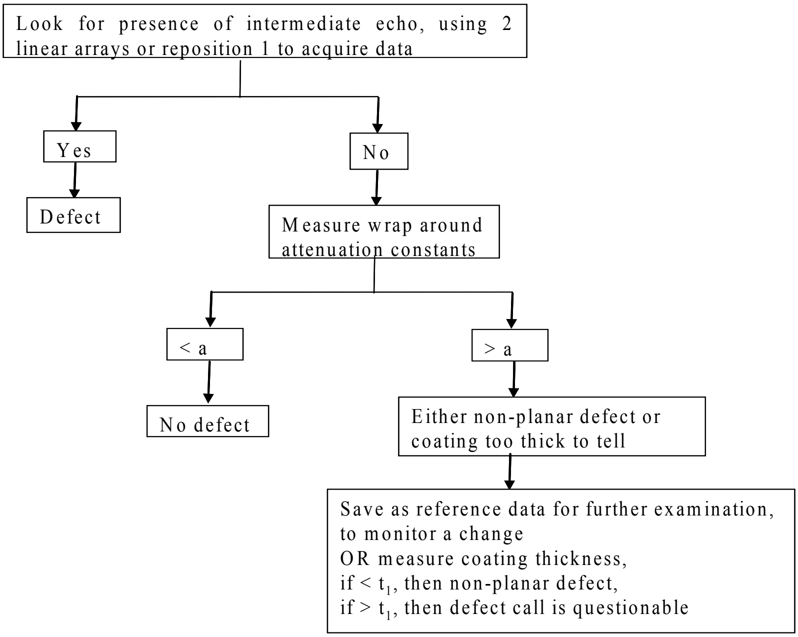


FIGURE 11. A test protocol for defect detection in a tar coated pipe using circumferential SH waves generated by a linear transducer array. This shows a dramatic accomplishment for the tar coated pipeline inspection.

CONCLUDING REMARKS

- Theoretical work has been carried out by developing dispersion curves and wave structures for circumferential guided waves in a pipe coated with a viscoelastic material.
- Wave structure analysis was conducted at selected frequencies, giving insight on defect inspection by looking at the energy distribution along the wall thickness direction. Both attenuation and wave structure studies suggest the use of low frequencies.
- A linear array transducer has been explored for defect detection in coated pipe. Defect reflection echo and attenuation of wrap around signal amplitudes are found to be two feasible features.
- A test protocol based on this study is recommended and summarized. Two linear arrays are suggested, or the repositioning of one, to acquire data.
- This study has shown an effective accomplishment for the defect inspection of a tar coated pipeline.

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