PHASED-ARRAY FOCUSING WITH LONGITUDINAL GUIDED WAVES IN A VISCOELASTIC COATED HOLLOW CYLINDER

W. Luo, J. L. Rose, J. K. Van Velsor, J. Mu

Department of Engineering Science & Mechanics, The Pennsylvania State University, University Park, PA 16802, USA

ABSTRACT. Guided wave phased-array focusing techniques have been studied and applied in the long-range guided wave inspection of industrial pipelines. Advantages include longer inspection distance, greater wave penetration power and higher detection sensitivity. For reasons of protection, safety and thermal efficiency, a large percentage of pipes are coated and/or encased and buried underground. A phased-array focusing study for guided waves is now considered on pipelines with viscoelastic coatings. In this paper, longitudinal guided wave focusing as well as axisymmetric wave propagation is studied in a bare pipe and a pipe with a viscoelastic coating. A finite element model is studied. First, an investigation on whether the coating has an affect on the axisymmetric guided wave propagation is reported. Based on the result of a single channel, phased array focusing with 8-channel segments is studied. This study provides a very useful tool and guidance for the analysis and examination of guided wave focusing in a real field pipeline under various coating and environmental conditions.

KEYWORDS: guided wave, phased array, focusing, finite element, multilayer, viscoelastic coating, ultrasonics, pipelines
PACS: *43.35.Zc, 81.70.Cv, 43.20.Mv, 43.35.Mr, 02.70.Dc

INTRODUCTION

Pipelines are used in almost every industry to provide large scale distribution of products, such as gas, oil, and water. Defective pipelines can cause fatal failures, property damage, and high litigation and replacement costs. Long range ultrasonic guided wave inspection with axisymmetric or phased array loading is an efficient and economical NDE method for pipeline defect inspection [1]. Viscoelastic coating (bitumen, epoxy) is widely used in industrial piping for corrosion protection. However, wave propagation and phased-array focusing in pipes coated with viscoelastic material has not been studied thoroughly.

In this work, finite element modeling using ABAQUS is used to study guided waves in a pipe with axisymmetric and phased array loading. A feasibility study of phased-array focusing with longitudinal waves in coated pipe is performed and the effect of the viscoelastic coating is analyzed in order to provide quantitative information on phased-array guided wave inspection ability.

CP820, *Review of Quantitative Nondestructive Evaluation Vol. 25,* ed. by D. O. Thompson and D. E. Chimenti

GUIDED WAVE PHASED ARRAY FOCUSING

Phased array focusing is realized by applying input time delays and amplitudes to an N-channel phased array. Focusing techniques can increase the impinging energy, locate defects, and enhance inspection resolution and propagation distance. Different from bulk wave phased array ultrasonics, the time delay and amplitude applied on each channel for guided wave phased array focusing in a pipe is a non-linear function of focal distance, pipe geometry, excitation source, and frequency. They can be calculated by a deconvolution based on the energy distribution profile of a single channel as shown in equations (1) to (4). See [2] for details.

$$H(\theta) \otimes A(\theta) = G(\theta), \tag{1}$$

$$A(\theta) = G(\theta) \otimes^{-1} H(\theta) = FFT^{-1}(1/\mathrm{H}(\omega)), \tag{2}$$

$$\text{Amplitude } A_i = |A(\theta)|_{\theta=\theta_i},$$

$$\text{Time delay } \Delta t_i = Phase\{A(\theta)|_{\theta=\theta_i}\} = -\phi_i / 2\pi f \tag{4}$$

where G is the expected function of focal energy profile, H is the angular profile of a single partially loaded channel, A is the discrete weight function for excitation channels.

FINITE ELEMENT MODEL FOR PHASED ARRAY FOCUSING STUDY

A finite element model, as shown in Figure 1, has been established for studying 8-channel phased array focusing in 10 inch schedule 40 pipe. The time delays and amplitudes were calculated using the above algorithm and summarized in Table 1. Axisymmetric waves can be modeled simply by setting the same time delay and amplitude for all 8 of the channels. A focusing result using the finite element model, seen in Figure 2, shows that focusing energy is about 5 times larger than the unfocussed axisymmetric loading case. The axial profile is also plotted in Figure 3 showing the displacement magnitude along the axial direction at zero degrees. The axial profile is a useful representation of the wave attenuation for the later attenuation studies in this paper.

TABLE 1. Signal amplitude and time delay for focusing at zero degrees at a 1.5 meter distance for the 100 kHz L(0,2) mode in a 10 inch schedule 40 pipe.

Element No.	1	2	3	4	5	6	7	8
Amplitude	1.000	0.933	0.769	0.726	0.610	0.726	0.769	0.933
Time Delay (μsec)	10.364	9.771	7.811	4.558	0.000	4.558	7.811	9.771

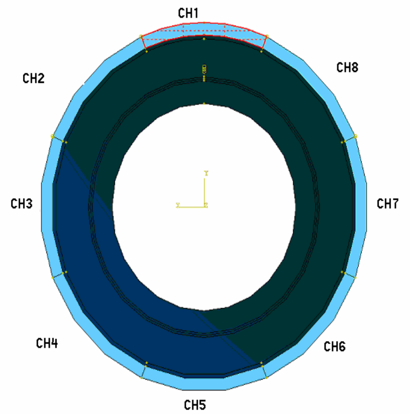
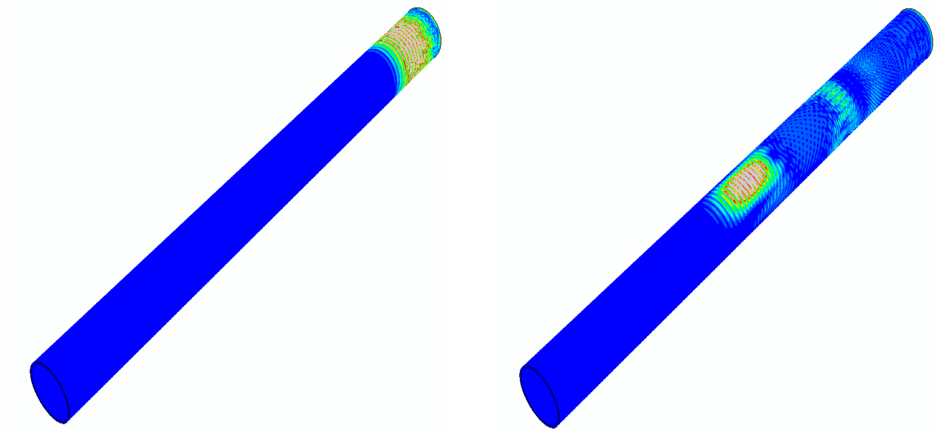


FIGURE 1. Finite element model for 8-channel phased array focusing in a 10 inch schedule 40 pipe.



(a) Beginning **(b)** Focusing

FIGURE 2. 8-channel phased array focusing at zero degrees at a 1.5 meter axial distance in a 3-meter-long 10 inch schedule 40 pipe at a frequency of 100 kHz, showing resulting displacement profiles at different focusing steps. Focusing realizes a significantly higher Energy (5×) compared to the axisymmetric case.

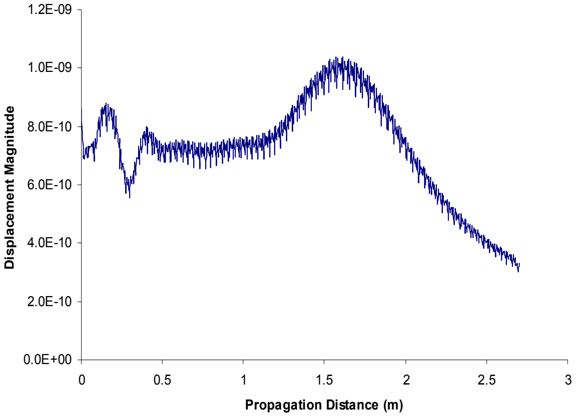


FIGURE 3. Axial profile at zero degrees in a 10 inch schedule 40 pipe of the 100 kHz L(0,2) mode in a 10 inch schedule 40 pipe with 8-channel phased array loading, showing the energy focused at the predetermined 1.5 meter distance.

VISCOELASTIC PROPERTY ESTIMATION

In order to study the wave propagation and phased array focusing in a viscoelastic coated pipe, the viscoelastic properties of the coating material must be estimated first. The following demonstrates how to calculate the viscoelastic properties from acoustic property measurement.

For a time harmonic case, according to the correspondence principle [3], the stress-strain relationship for a viscoelastic material is changed by using the complex, viscoelastic modulus. Therefore, the complex elastic modulus E^* can be expressed as:

$$E^* = E' + iE'' \tag{5}$$

where E' is the storage modulus which defines the material stiffness, and E'' is the loss modulus which defines the energy dissipation of the material.

For one-dimensional wave propagation in a viscoelastic material, the complex velocity $c^*(\omega)$ can be expressed as in equation (6):

$$c^*(\omega) = \frac{1}{\dfrac{1}{c(\omega)} - i\dfrac{\alpha(\omega)}{\omega}} \tag{6}$$

where $c(\omega)$ is the phase velocity, and $\alpha(\omega)$ is the attenuation coefficient. The velocity is specified to be complex and frequency dependent due to the viscoelastic material properties. Phase velocity $c(\omega)$ and the attenuation constant $\alpha(\omega)$ can be defined from the wave velocity as follows:

$$c(\omega) = \left(\mathrm{Re}\left(1 / c^*(\omega)\right)\right)^{-1} \tag{7}$$

$$\alpha(\omega) = -\omega \,\mathrm{Im}\left[\frac{1}{c^*(\omega)}\right] \tag{8}$$

The terms $c(\omega)$ and $\alpha(\omega)$ can be experimentally determined and then $c^*(\omega)$ can be acquired by equation (6). The complex shear modulus G^* (also the 2nd Lamé constant μ^*) is calculated as in equation (9):

$$G^* = \mu^* = c_2^{*2} \cdot \rho = \left[\frac{1}{c_2(\omega)} - i\frac{\alpha_2(\omega)}{\omega}\right]^{-2} \cdot \rho = \left(\frac{c_2\omega}{\omega - ic_2\alpha_2}\right)^2 \cdot \rho \tag{9}$$

where the subscript 2 indicates the variables for shear waves and ρ represents the density of the material.

Young's modulus is expressed in equation (10):

$$E^* = \left[\frac{3-4\left(\frac{c_2^*}{c_1^*}\right)^2}{1-\left(\frac{c_2^*}{c_1^*}\right)^2}\right] G^* = \left[\frac{3-4\left(\frac{c_2^*}{c_1^*}\right)^2}{1-\left(\frac{c_2^*}{c_1^*}\right)^2}\right] \cdot c_2^{*2} \cdot \rho = \left[\frac{3-4\left(\frac{c_2\omega - ic_1c_2\alpha_1}{c_1\omega - ic_1c_2\alpha_2}\right)^2}{1-\left(\frac{c_2\omega - ic_1c_2\alpha_1}{c_1\omega - ic_1c_2\alpha_2}\right)^2}\right] \cdot \left(\frac{c_2\omega}{\omega - ic_2\alpha_2}\right)^2 \cdot \rho \tag{10}$$

where the subscript 1 indicates the variables for longitudinal waves. Therefore, the complex modulus can be calculated from the measured velocities and attenuation for longitudinal and shear waves.

Some typical viscoelastic coating materials are selected for this study [4] and their measured elastic and viscoelastic properties are shown in Table 2. The damping properties, calculated using equation (9)-(10), are shown in Table 3.

GUIDED WAVE MODELING IN A COATED PIPE

With the calculated viscoelastic properties as inputs, the guided wave propagation and scattering in coated pipe can be modeled as shown in Figure 4 for 100 kHz L(0,2) waves. It is very exciting to see that, from the angular profile shown in Figure 5, focusing is achieved very well in a pipe coated with highly viscoelastic bitumastic materials; although, there is a loss of signal amplitude. Axial profiles for focusing are plotted using the output signal data of the model and compared with the results of axisymmetric loading in order to qualitatively study the focused wave behavior. The amplitude comparison of axisymmetric waves and focusing in bare and coated pipe are shown in Table 4 with a general finding that focusing increases the displacement amplitude by about 8 dB (16 dB for energy) for the studied focused distance. The feasibility of focusing in a coated pipe is also confirmed by experiment as shown in Figure 7.

TABLE 2. Elastic and viscoelastic material properties.

Material	c_1 $(km/\sec)$	α_1/ω	c_2 $(km/\sec)$	α_2/ω	ρ (gm/cm^3)
E&C 2057 / Cat9 Epoxy	2.96	0.0047	1.45	0.0069	1.60
Mereco 303 Epoxy	2.39	0.0070	.99	0.0201	1.08
Bitumastic 50 Coating	1.86	0.0230	0.75	0.2400	1.50

TABLE 3. Calculated material damping properties.

Material	E* (Pa)	G* (Pa)
E&C 2057 / Cat9 Epoxy	9.03E9+1.92E8i	3.36E9+6.73E7i
Mereco 303 Epoxy	2.95E9+1.92E8i	1.06E9+4.27E7i
Bitumastic 50 Coating	2.18E9+7.6E8i	7.66E8+.85E8i

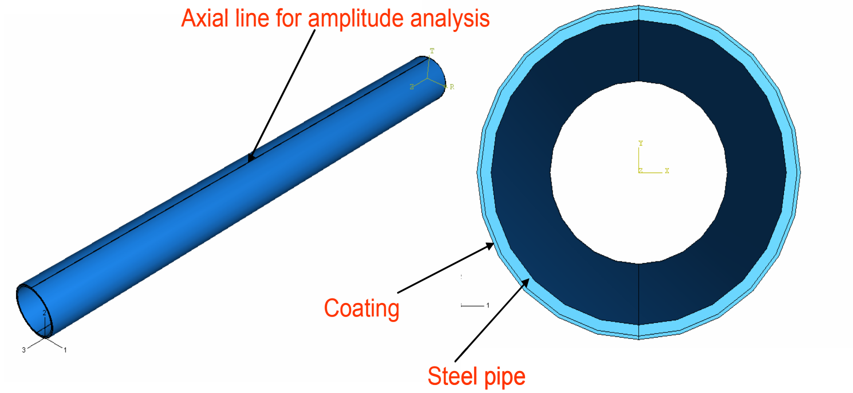
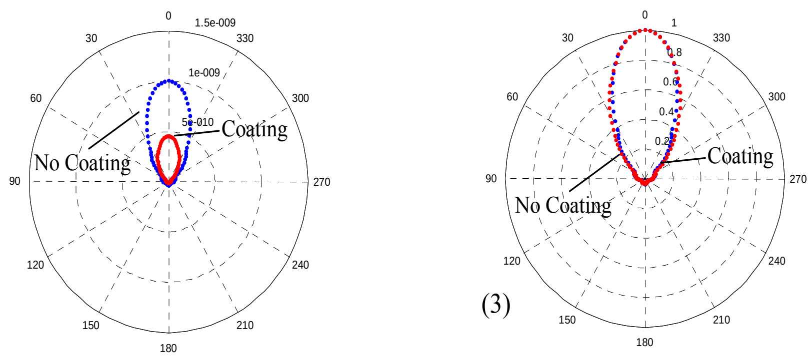
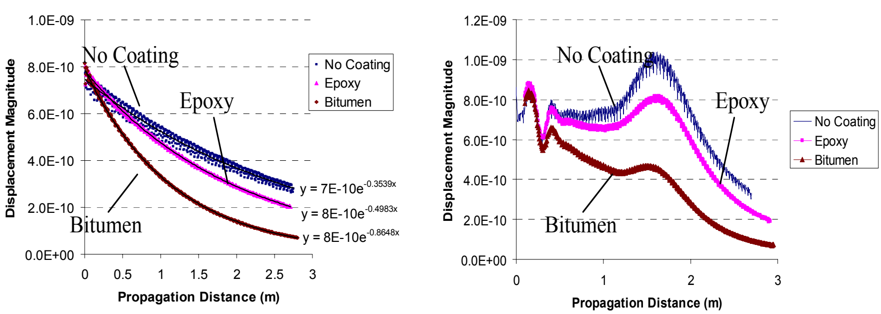


FIGURE 4. Finite element model for guided wave propagation analysis in a 3 meter long 10 inch schedule 40 pipe coated with 3 mm viscoelastic material.



(a) Before Normalization **(b)** After Normalization

FIGURE 5. Angular Profile at the focal point for a bare pipe (10 inch schedule 40) and a pipe coated with 3 mm bitumen with 100 kHz L(0,2) waves focused at a distance of 1.5 meters, showing that coating introduces some attenuation but that the profile shape stays the same.



(a) **(b)**

FIGURE 6. Angular profile for 100 kHz L(0, 2) wave with (a) axisymmetric loading;(b)focused at a distance of 1.5 meters, in 10 inch schedule 40 pipes with no coating, 3 mm epoxy and 3 mm bitumen. It shows that focusing increases the amplitude greatly compared to an axisymmetric wave.

TABLE 4. Amplitude gain by focusing at a focal point at a distance of 1.5 meters.

Material	Amplitude at the focal point		Amplitude Ratio	Gain (dB)
	Focusing	Axisymmetric		
No Coating	1.04E-9	3.97E-10	2.62	8.37
Mereco 303 Epoxy	8.18E-10	3.62E-10	2.26	7.08
Bitumastic 50 Coating	4.71E-10	2.01E-10	2.34	7.38

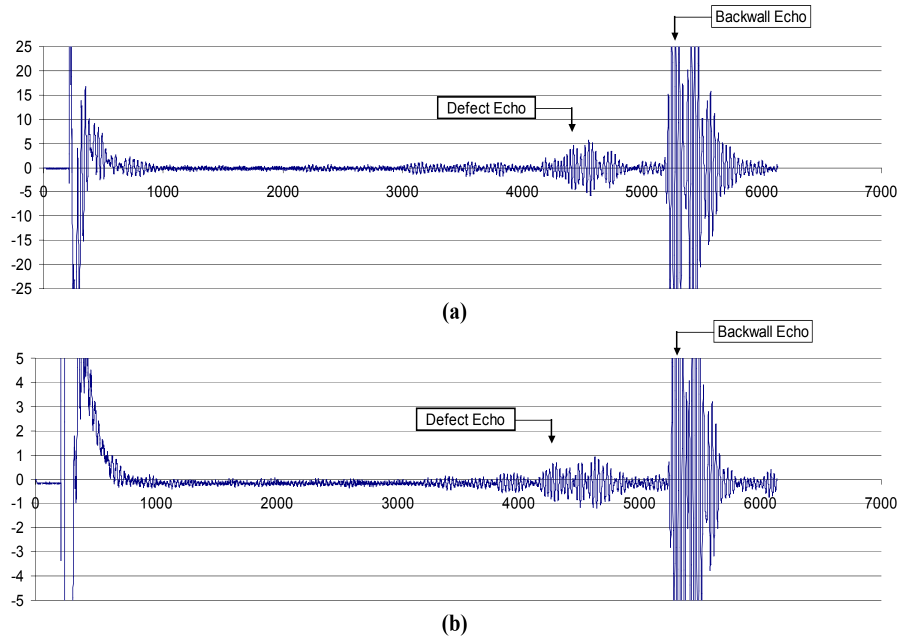


FIGURE 7. Focusing experiments on (a) a bare pipe and (b) a tar-coated pipe with a 6mm deep, 3.26% CSA, 63% through-wall saw cut in both, showing focusing in tar-coated pipe.

CONCLUDING REMARKS

- A two layer 3-D finite element model has been developed to study the wave propagation and focusing in bare pipe and coated pipe.
- Viscoelastic properties of coatings were calculated by the measured coating acoustic properties and used as inputs to the finite element model to study the coating effect on guided wave propagation and focusing in a coated pipe
- It has been found that viscoelastic coating has no effect on focusing capability although there is an amplitude loss which is dependent on coating viscosity and frequency.
- Modeling studies show that phased array focusing with longitudinal waves increases the signal energy by 16 dB for a certain propagation distance, indicating a much longer propagation distance and also improved defect detection sensitivity.

REFERENCES

1. Rose J. L., *J. Press. Vess. Tech.*, **124**(8), 273-282, 2003.
2. Li, Jian, Rose, J. L., *IEEE Trans. Ultras. Ferroel. Freq. Contr.,* **49**, 1720-1729, 2002.
3. Christensen R. M., 1981, *Theory of Viscoelasticity: An Introduction*, Academic Press, New York.
4. Barshinger, J. N., Rose, J. L., *IEEE Trans. Ultras. Ferroel. Freq. Contr.,* **51**(11), 2004.