Ultrasonic Guided Wave Phased Array Inspection of Pipelines

S. Palit Sagar[a], Jia Jerry Hua and Joseph L Rose[b]

[a]Scientist EII, Materials Science & Technology Division, National Metallurgical Laboratory, Jamshedpur 831007, India

[b]Paul Morrow Professor, Department of Engineering Science & Mechanics, The Pennsylvania State University, PA 16802,USA

ABSTRACT

Piping systems are often inspected ultrasonically to ensure safety. This can be accomplished by a series of point to point tests from the outside surface of the pipe. If coating covers the pipe, as is often the case, access to the outside surface requires removal of the coating to perform the test, and then re-installation when testing is complete. Removal and reinstallation of coating is not only time consuming but in most cases it is prohibitively expensive too. Ultrasonic guided waves provide an attractive alternative solution to the basic bulk wave ultrasonic test. Using Guided Waves, a probe can be applied to the pipe at a single location and several meters of the pipe can be inspected. The coating is only removed where the probe is applied. This paper describes the visco-elastic properties of two different coating materials: Bitumen tape and wax tape is considered, an FEM simulation of the propagation of axisymmetric guided waves through bare and coated pipes having different coating thicknesses. The ABAQUS FEM code is used and validation of FEM simulation results through experiments in bare and coated pipes using guided wave inspection system is reported.

1. INTRODUCTION

The oil, gas, chemical and petro-chemical industries operate hundreds of kilometres of pipelines for transporting chemicals, oil, water, and other necessities. Testing of these large structures using conventional bulk ultrasonic wave techniques is slow because the test region is limited to the area immediately surrounding the transducer. Therefore, scanning is required if the entire structure is to be tested. Moreover, a high proportion of industrial pipelines are insulated using visco-elastic coatings, so that even external corrosion cannot readily be detected without the removal of the coating, which in most cases is prohibitively expensive. Ultrasonic guided waves provide an attractive alternative solution to this problem [1-7]. "Guided Waves" are ultrasonic waves guided by the geometry of the object in which they propagate. Due to decreased attenuation loss, these waves transmit along the whole circumferential section of the pipe while propagating in the axial direction. These waves travel across the straight stretches of pipe to several meters from a single point using a pulse-echo transducer bracelet wrapped around a pipe [6]. Current long-range guided wave techniques for pipeline inspection include axisymmetric and non-axisymmetric waves with partial loading and phased array focusing [5, 6]. It has been shown by Li and Rose [5] that among these two techniques, the focusing technique can increase energy impingement, locate defects, and greatly enhance the inspection sensitivity and propagation distance of guided waves, thus consequently reducing inspection costs. Viscoelastic coatings, such as bitumen and wax tapes, are commonly used for protection against corrosion in the pipeline industry. The presence of viscoelastic coating results in changes of guided wave propagation characteristics. Because of a variation of coating materials and the complexity of the wave mechanics in a viscoelastic coated multilayered structure, many aspects and questions on guided wave inspection in coated pipes are still untouched and remain quite challenging. In this work, a three-dimensional finite element method is studied for modeling guided waves in a bare pipe and also for Bitumen (BT) and Wax tape (WT) coated pipes. Visco-elastic properties of the BT and WT materials were studied and the experiments were performed on 4inch bare and BT and WT coated steel pipes using 8 channel axysymmetric torsional guided waves to validate the FEM results for practical applications.

2. SELECTION OF APPROPRIATE GUIDED WAVE MODE

Guided waves in the axial direction of a hollow cylinder include longitudinal and torsional waves with both axisymmetric and nonaxisymmetric modes. Typical dispersion curves in a bare pipe are plotted in Fig. 1, showing various wave modes in a pipe.

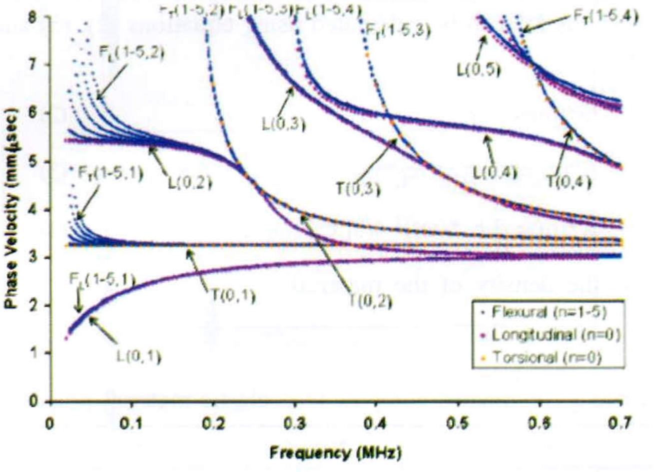

Fig. 1 : Phase velocity dispersion curves of axysymmetric and flexural modes in 10-in. schedule 40 steel pipes [5]

Table 1: Elastic Properties of coating materials

Material	c_L *(mm/ms)*	c_S *(mm/ms)*	$\alpha_L(\omega)/\omega$ *(1/mm)*	$a_S(\omega)/\omega$ *(1/mm)*	*Density* kg/m^3	*Youngs Modulus (GPa)*	*Poissons's Ratio*
BT	2.27	0.77	.047	.47	1200	2.04	0.43
WT	2.04	0.781	.021	.21	1000	1.725	0.41

Hence a key element of the inspection system is the selection and exploitation of a single mode. Indeed, even with a single mode, great care is needed for the correct identification of the reflections from defects and from normal pipe features such as welds. Therefore, although troublesome to achieve, it is essential to design the transducers and the signal to excite only the chosen mode. The mode that was chosen for excitation in the inspection system is the axially symmetric L(0,2) mode for longitudinal waves and the T(0,1) mode for torsional waves at about 40 kHz. This mode is very attractive for testing for several reasons: it is practically non-dispersive over a wide bandwidth around this frequency that is to say its velocity does not vary significantly with frequency, so that the signal shape and amplitude are retained as it travels.

3. ELASTIC AND VISCO-ELASTIC PROPERTIES EVALUATION OF BITUMEN AND WAX TAPE

Ultrasonic longitudinal (c_L) and shear (c_S) velocities of BT and WT materials were determined by a bulk ultrasonic wave measuring technique. The Young's modulus and the Poisson's ratio of the coated material were determined from the measured c_L and c_S and are furnished in Table 1.

The measured bulk wave velocities c(ω) and attenuation constants α(w) can be used to calculate the complex frequency dependent wave velocity c*(ω) using the equation(1) [8]:

$$c^*(\omega) = 1/((1/c(\omega)-i\alpha_L(\omega)/\omega) \qquad (1)$$

In a similar manner, the complex shear modulus G*, the complex Young's modulus E* and the complex bulk modulus K* can be calculated using equations (2), (3) and (4):

$$G^*(\omega)=c_s{}^{*2}r \qquad (2)$$

$$E^*(\omega)=[(3-4(c_S{}^*/c_L{}^*)^2)/(1-(c_S{}^*/c_L{}^*)^2]G^* \qquad (3)$$

$$K^*(\omega)= r[\, c_L{}^*(\omega)]^2-4/3[\, c_S{}^*(\omega)]^2r \qquad (4)$$

r is the density of the material.

The real part of eqns (2), (3) and (4) are related to the stiffness of the viscoelastic material, while the complex part is associated with the energy dissipation of the material. Table 2 lists the viscoelastic properties of BT and WT.

4. FEM SIMULATION

4.1 Wave propagation models in bare and coated pipes

The explicit direct integration method works the best for wave propagation problems due to its lower computational cost [3]. In this work, a FE package ABAQUS/Explicit was used for the modeling of guided wave propagation and focusing in pipes. A sample problem is discussed. The pipe model length is 3.2 m and the pipe wall thickness is 9 mm.

The excitation frequency can be realized by using a windowed sinusoidal signal as the time-dependent amplitude of the pressure, also called a loading function. The first step in selective excitation is to use a narrow band signal to have good signal strength and to avoid dispersion over long propagation distances. However, too many cycles may result in a long time span. Usually 5–15 cycles are used. In this work a 40 kHz tone burst of 7 cycles in a Hanning window is used. A typical time record for a 7 cycle hanning windowed signal is shown in Fig. 2.

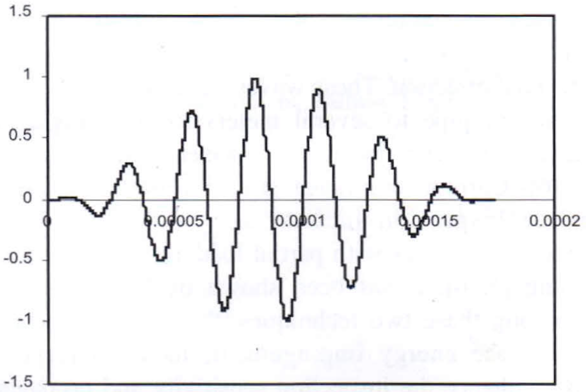

Fig. 2 : 40 kHz 7 cycles hanning windowed tone burst signal

Table 2 : Estimated complex viscoelastic material properties of the coating materials

Coating	c_L**(mm/ms)*	c_S**(mm/ms)*	*G*(Pa)*	*E*(Pa)*	*K*(ω)*
BT	2.177+0.225i	0.7514+0.311i	5.61e8+5.60e8i	1.67e9+1.56e9i	4.876e9+4.28e8i
WT	1.996+0.084i	0.7504+0.1213i	5.48e8+1.82e8i	1.56e9+4.92e8i	3.247e9+0.92e8i

4.1.1 FE modeling of bare and BT and WT coated pipe with torsional guided waves

A 40 kHz Hanning windowed 7 cycles tone burst signal was applied in the circumferential direction at one end of the test pipe and the signal was received at the other end of the pipe as depicted in Fig. 3.

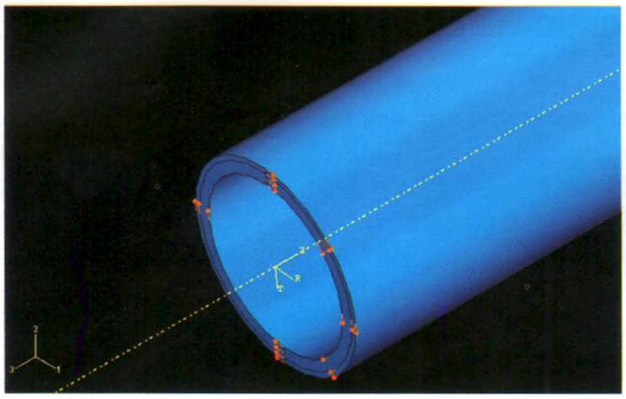

Fig. 3 : Simulated coated pipe with axial load applied at one end

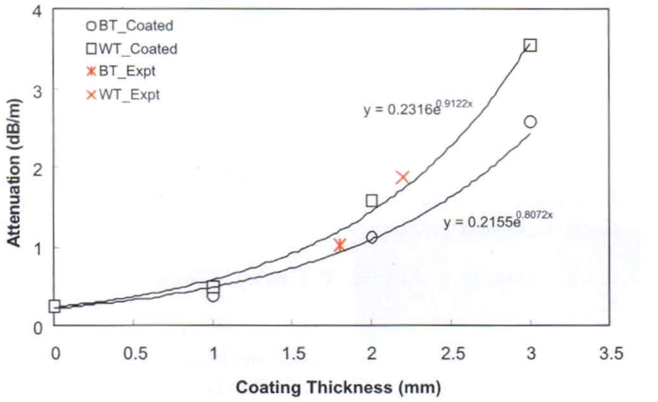

Fig. 4 : Variation of wave attenuation with coating thickness for BT and WT coated steel pipes

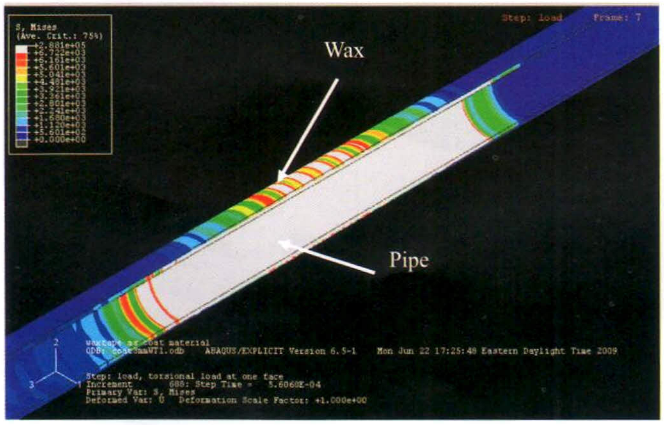

Fig. 5 : Contracted view of the pipe showing energy leakage from the pipe wall into the wax coating

From the received signals, wave attenuation was determined for bare and BT and WT coated pipes with 1mm, 2mm and 3 mm coating thicknesses and plotted in Fig. 4.

Fig. 6 : Photographs of tested bare and BT and WT coated pipes

Result shows that the wave attenuation increases with coating thickness and the attenuation is higher in WT coated pipe compared to the BT coated pipe. A contracted view of Von-Mises stress wave propagation through simulated 3mm WT coated 3.2m long steel pipe is presented in Fig. 5 to show the stress leakage from the pipe into the coating.

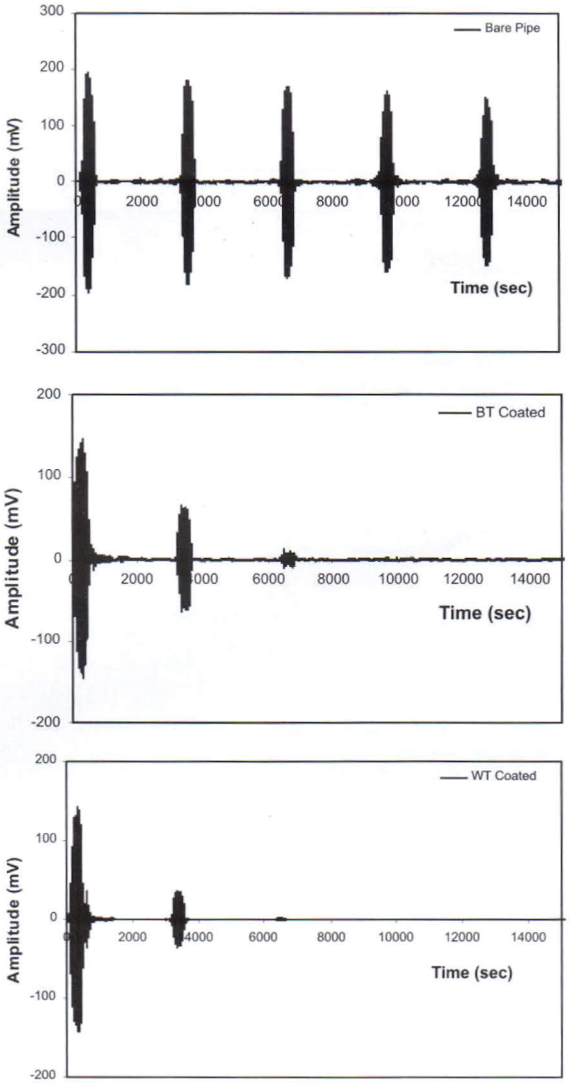

Fig. 7 : Received signals from bare, BT and WT coated 3.2m long pipe using low frequency torsional mode guided wave

4.1.2 Experimental validation of FEM simulation

Experiments were performed on 3.2m long, 4In. Schedule40 bare, 1.8 mm bitumen tape coated and 2.2 mm wax tape coated steel pipes using the 4 channel low frequency ultrasonic guided wave system. Figure 6 shows the photographs of the test pipes and the probe assembly of the test system.

The guided wave in a torsional mode was used and the test results of bare, BT coated and WT coated pipes at a frequency of 40 kHz are shown in Fig. 7.

Wave attenuation as determined from the received signals for Bare, BT and WT coated pipes were 0.1dB/m, 1.01dB/m and 1.87dB/m respectively. Table 4 gives the comparison of the wave attenuation as determined from FEM simulation and experimental data. The experimentally determined attenuation (dB/m) values were incorporated in the graph as shown in Fig. 4.

Table 3: Comparison of FEM simulation and experimental data of wave attenuations in bare and BT and WT coated pipe

Material	*Coating thickness (mm)*	*Attenuation dB/m*	
		FEM simulation	*Experimental*
Bare	0	0.25	0.1
BT Coated	1.8	0.92	1.01
WT Coated	2.2	1.71	1.87

5. CONCLUSIONS

Torsional mode guided wave ultrasonic was used to inspect the 3.2m long 4inch Schedule40 steel pipe with bitumen and wax tape coating of various thicknesses. FEM simulation shows that the single probe positioned guided wave technique can inspect the long coated pipes without removal of coatings, which is otherwise not possible by point to point inspection using bulk ultrasonic measurement technique. Experimental results successfully validate the applicability of guided wave technique in long range pipe inspection with visco-elastic coatings.

ACKNOWLEDGEMENTS

This work is a part of the Raman Research Fellowship of the principal author, sponsored by Council of Scientific & Industrial Research (CSIR), Govt. of India. Authors also acknowledge the help from the graduate students of Ultrasonic group, Dept. of Engg. Science & Mechanics, The Pennsylvania State University and staffs of FBS Inc., Pennsylvania for carrying out guided wave experiments.

REFERENCES

1. Joseph L Rose, *Ultrasonic Waves in Solid Media*, Cambridge University Press, Book
2. J. L. Rose, *IEEE Ultrasonics Symposium*, (1995) 761
3. Wei Luo and J. L. Rose, *J. Acoust. Soc. Am.* 121 (2007) 1945
4. H. Kwun, S.Y. Kim, M.S. Choi, S.M. Walker, *NDT&E International* 37 (2004) 663
5. J. Li and J. L. Rose, *J. Acoust. Soc. Am.* 109 (2001) 457
6. J. Li and J. L. Rose, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control,* 48 (2002)761
7. M.J.S. Lowe, D.N. Alleyne, P. Cawley, *Ultrasonics,* 36 (1998) 147
8. Mu Jing, "Guided Wave Propagation and Focusing in Viscoelastic Multilayered Hollow Cylinders", Ph. D thesis, Engineering Mechanics, The Pennsylvania State University, 2008