17th World Conference on Nondestructive Testing, 25-28 Oct 2008, Shanghai, China

Recent Advances on Guided Waves in Pipe Inspection

Joseph L. ROSE [1], Jing MU [2], Younho CHO [3]

[1] Department of Engineering Science and Mechanics, The Pennsylvania State University,
University Park, PA 16802
Phone: +1 814-863-8026; email: jlresm@engr.psu.edu
[2] Department of Engineering Science and Mechanics, The Pennsylvania State University,
University Park, PA 16802
Phone: +1 814-863-9394; email: jxm1006@engr.psu.edu
[3] School of Mechanical engineering, Pusan National University, San 30, Jangjeon-dong,
Gumjeoing-gu, Pusan, 609-705, Republic of Korea
Phone: +82 51-510-2323; email: mechcyh@pusan.ac.kr

Abstract

Guided waves have been increasingly used in nondestructive evaluations. Guided waves have shown to be specially promising in the testing of pipelines and tubing systems due to the ability of propagating long distances. Recent advances on guided wave pipe inspection focus on the understanding and utilization of guided wave flexural modes. This paper discusses and compares the technologies currently employed in pipe testing. The phased-array guided wave focusing technique in pipes will be particularly addressed because of its ability of enhancing penetration power. Taking into account the fact that many pipelines are covered with protecting viscoelastic coatings, the newly developed guided wave focusing technique in viscoelastic coated pipes will be presented in detail.

Keywords: guided wave, focusing, pipe, coating

1. Introduction

Guided waves are ultrasonic waves traveling in bounded structures. The theories of guided waves have been explored for decades and can be found in many text books[1-3]. Guided waves have the potential of propagating long distances with little attenuation. Due to this advantage, guided waves techniques are expandingly adopted in nondestructive testing[4-5]. Especially for piping and tubing systems, it is possible to generate guided waves from a single probe position, while providing full ultrasonic energy coverage of the whole structure. This makes guided wave a good candidate for rapid and economical inspection of pipelines.

The methods that are currently used in guided wave pipe testing include axisymmetric wave inspection, frequency and angle tuning (FAT) technique[6], and guided wave phased array focusing technique[7]. Axisymmetric wave inspection provides fast and easy pipe inspection. FAT can be used where only limited access to the circumference of a pipe is allowed. The guided wave focusing technique utilizes a phased array wrapping around the circumference of a pipe. By adjusting the time delays and output voltage levels of the channels in the phased array, guided wave energy can be tuned to focus at any predetermined position in a pipe[7-8]. Compared to axisymmetric guided wave inspection, the guided wave focusing technique does not only enhance penetration power, but also provide direct circumferential resolution and sizing ability[9]. In fields, long range pipe imaging can be easily achieved by performing circumferential scans along axial distance[10].

In applications, pipelines are often covered by viscoelastic coatings for various protection purposes. The guided wave energy sent to a pipe will partially leak into the coating. This makes the guided wave propagation characteristics in a viscoelastic coated pipe different from that in an elastic bare pipe. Understanding guided wave propagation characteristics in viscoelastic coated pipes becomes quite essential for mode control and intelligent usage of proper guide modes in coated pipe testings.

This paper presents the guided wave propagation and focusing mechanism in both bare and viscoelastic coated pipes[11]. Theoretical calculation and Finite Element (FE) modeling of guided wave focusing in viscoelastic coated pipes are given. Comparisons of using coated pipe focusing parameters and the corresponding bare pipe parameters to focus guided wave energy in a coated pipe are also discussed.

2. Guided wave focusing mechanism in viscoelastic coated pipes

The wave propagation in a free viscoelastic coated pipe can be solved using a Semi-Analytical Finite Element (SAFE) Method[11]. In the SAFE formulation, the coated pipe structure is discretized in the radial direction, while analytical representations are used in the circumferential and axial directions. Compared to analytical methods, SAFEM has the ability to deal with wave guides with complex cross sections. In the mean time, compared to pure Finite Element Method (FEM), the matrix size in SAFEM is reduced by incorporating analytical representations.

Base on the free wave solutions, the angular profile which describes the displacement amplitude distribution around the pipe circumference for a certain source loading can be calculated by the Normal Mode Expansion method[12]. The angular profiles for an 8 in. schedule 40 steel pipe coated with 2 mm Cat9 expoxy under a 45° axial direction source loading at 95 kHz are plotted in Fig. 1 with blue solid lines. Also plotted in Fig. 1 are the angular profiles for the corresponding bare pipe: the 8 in. schedule 40 steel pipe under the same source loading and frequency with red dash-dotted lines. The angular profiles are plotted for two different axial distances 4.75 and 5.6m from the source location for each case. The material parameters used in the calculation is listed in Table 1.

Table 0-1: Material properties

Material	C_L (mm/μs)	$\frac{\alpha_L}{\omega}$ (μs/mm)	C_S (mm/μs)	$\frac{\alpha_S}{\omega}$ (μs/mm)	ρ (g/cm^3)
Steel	5.85	-	3.23	-	7.86
E&C 2057 / Cat9 expoxy	2.96	0.0047	1.45	0.0069	1.6
Bitumastic 50	1.86	0.023	0.75	0.24	1.5

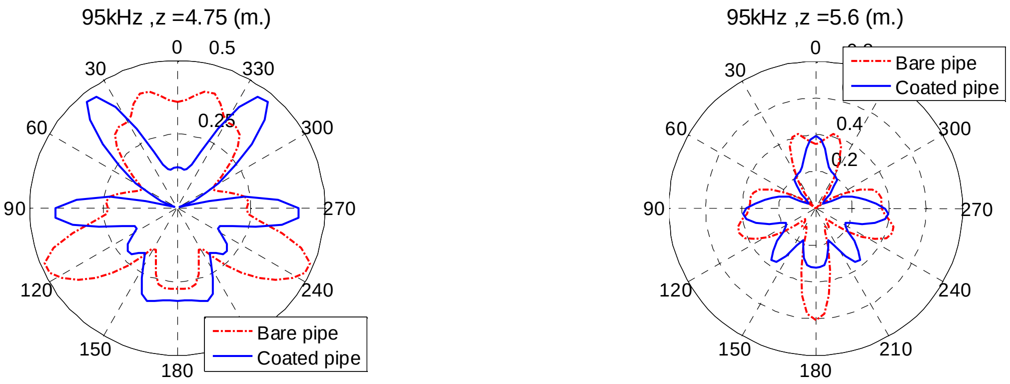

Figure 1. Blue solid lines: Angular profile of a 45º axial direction source loading on an 8 in. schedule 40 steel pipe coated with 2 mm Cat9 expoxy. Red dash-dotted lines: Angular profile of a 45º axial direction source loading on an 8 in. schedule 40 steel pipe. The frequency is 95 kHz. The axial distances for the plots on the left and right columns are 4.75 and 5.6 m. respectively.

As can be seen from Fig. 1, the existence of the viscoelastic coating changes the wave field distribution in the pipe. This can be expected since the incorporation of the coating layer to the bare pipe modifies the boundary conditions of the problem. Another effect of the coating layer is the attenuation induced by the viscoelastic material. In the coated pipe case shown in Fig. 1, the attenuation effect is not significant, since the coating material is not very attenuative and the axial distances are not very long. Given enough propagation distance, the wave energy will eventually be absorbed by the viscoelastic coating.

Since the existence of coating layer modifies the wave field distribution in the corresponding bare pipe, it can also be expected that the phased array focusing parameters in a coated pipe may differ from those calculated from the corresponding bare pipe. Fig. 2 shows the comparison among the angular profile of axisymmetric wave L(0,2) (green dashed lines), the focused profiles in an 8 in. schedule 40 steel pipe coated with 2 mm Cat9 expoxy using the coated pipe parameters (blue solid lines) and the corresponding bare pipe parameters (red dash-dotted lines). The number of channels in the phased array is 8. The focusing frequency is 95 kHz and the focal distances are 4.75 and 5.6 m, as those used in the partial loading profiles in Fig. 1.

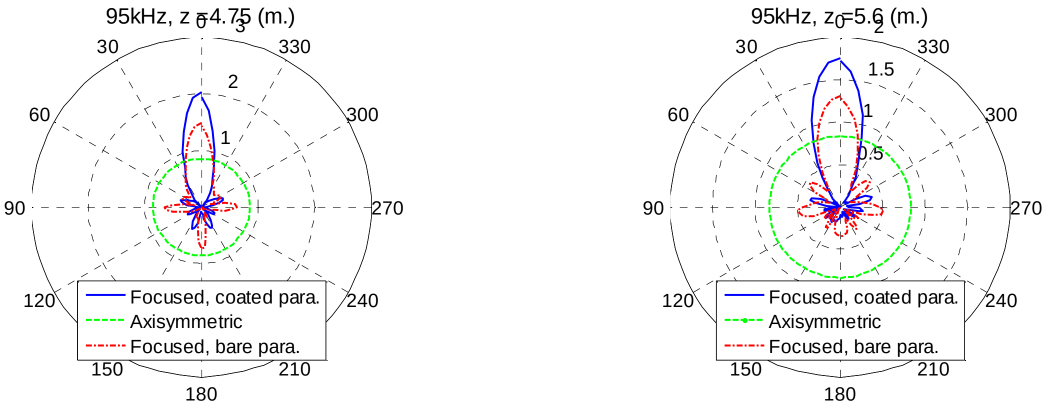

Figure 2. Blue solid lines: Longitudinal L(n,2) 8 channel focusing profiles in an 8 in. schedule 40 steel pipe coated with 2 mm Cat9 expoxy. Red dash-dotted lines: Longitudinal L(n,2) 8 channel focusing profiles in an 8 in. schedule 40 steel pipe. Green dashed lines: Axiymmetric wave L(0,2) angular profiles. The frequency is 95 kHz. The focal distance is 4.75 m. for the left column and 5.6 m. for the right column.

In Fig. 2, the exited amplitude for the axisymmetric wave L(0,2) and the maximum amplitude factor used in focusing is one. It can be clearly seen from Fig. 2 that the amplitudes of the axisymmetric wave L(0,2) are less than one after propagating 4.75 and 5.6 m. It can also be observed that the corresponding bare pipe focusing parameters can still focus a certain amount of energy in the coated pipe. However, the focusing parameters calculated directly from the coated pipe structure focus energy best. The coated pipe focusing parameters provide better penetration power and less side lobes than the corresponding bare pipe focusing parameters, as well as more than 6 dB improvement compared to axisymmetric wave inspection.

3. Finite Element Simulation

FE modeling is now widely adopted as a suitable tool to analyze problems with complex structures. It is also convenient to use FEM as numerical experiment to visualize physical phenomenon and to verify theories. In this work, the commercial software Abaqus is used to simulate guided wave focusing in coated pipes. The process of modeling will be discussed below.

In building the model, the whole cylindrical structure is first constructed. The cylinder is then partitioned into two sections, one pipe section and one coating section, as illustrated in Fig. 3. In the modeling, the loading area is defined at the edge for convenience. The partition for the 8 channel loading is also shown in Fig. 3. The loading is in axial direction denoted by arrows in orange. The structure is meshed with the maximum length of the elements less than one-eighth of the wavelength. The time steps in calculation can be automatically decided by Abaqus. The viscoelastic and elastic material property definitions in Abaqus are used to define the materials used in the pipe layer and coating layer. The pipe is 8 in. schedule 40 made of steel. The material used in the coating layer is bitumastic 50 with a thickness of 1 mm. The properties of bitumastic 50 can be found in Table 1. A 6 cycle toneburst at a center frequency of 60 kHz is used in the excitation.

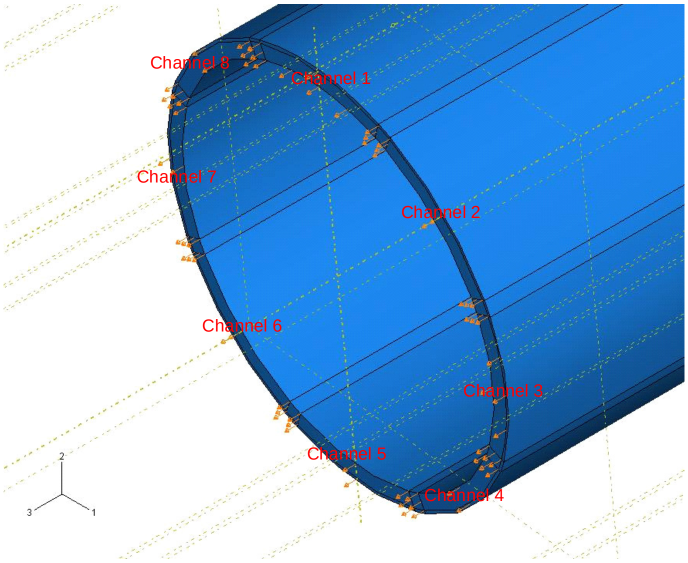

Figure 3. Illustration of the coated pipe configuration.

The guided wave focusing modeling results using the focusing parameters calculated from the 8 in. schedule 40 steel pipe coated with 1 mm. bitumastic 50 is shown in Fig. 4. The designed focal distance is 5.6 m, as pointed out by the black arrow in Fig. 4. It can be seen from Fig. 4 that the guided wave energy is well focused in the predetermined focal location.

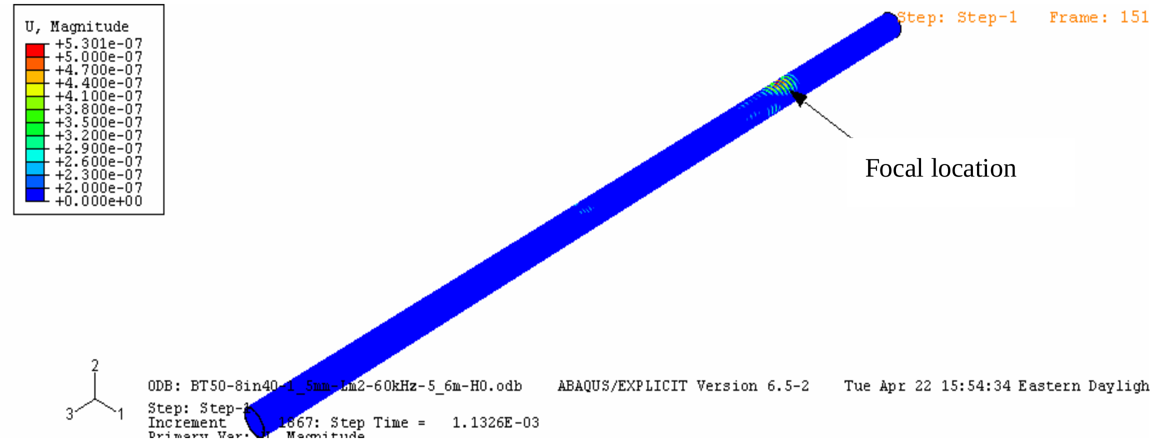

Figure 4. FE modeling of guided wave focusing in a coated pipe. Pipe size: 8 in. schedule 40 steel. Coating: 1-mm bitumastic 50. The designed focal distance is 5.6 m. 8 channel longitudinal focusing is used.

4. Conclusion

This paper summarizes the guided wave techniques currently used in pipe nondestructive testing with an emphasis on the guided wave focusing technique. The previously develop guided wave focusing technique in elastic bare pipes provides higher penetration power and better circumferential resolution. Facing the fact that most pipelines are coated with viscoelastic materials, this paper pushes the guided wave focusing technique forward by taking into account the effect of viscoelastic coating layers. Comparison between the focused profiles in coated pipes using the modified coated pipe parameters and the corresponding bare pipe parameters shows that the modified coated pipe parameters focus guided wave energy better in coated pipes. Finite element modeling is also used in verifying the coated pipe focusing parameter. Excellent focusing effect is obtained in the model.

References

[1] Achenbach, J. D., 1984, *Wave Propagation in Elastic Solids*, North-Holland Publishing Co., New York, NY.

[2] Graff, K. F., 1991, *Wave Motion in Elastic Solids*, Dover Publications Inc., New York.

[3] Rose, J. L., 1999, *Ultrasonic Waves in Solid Media*, Cambridge University Press.

[4] Alleyne, D. N. and Cawley, P. "Long range propagation of Lamb waves in chemical plant pipework," *Materials Evaluation*, vol.45, pp.504-508, 1997.

[5] Rose, J.L., "A baseline and vision of ultrasonic guided wave inspection potential," ASME Journal of Pressure Vessel Technology, 2002, vol. 124, pp. 273-282.

[6] Zhang, L, Rose, J.L., and Gavigan, "Natural Focusing Inspection for Pipes by Frequency Tuning", *Proceedings of QNDE*, Vol. 24, pp. 1557-1562, 2004.

[7] Li, J., and J. L. Rose, "Angular-profile tuning of guided waves in hollow cylinders using a circumferential phased array", IEEE Trans. Ultrason., Ferroelect., Freq. Contr., 49(12), 1720-1729, 2002.

[8] Sun, Z., Zhang, L., Rose, J.L., 2005, "Flexural Torsional Guided Wave Mechanics and Focusing in Pipe," ASME Transactions Journal of Pressure Vessel Technology, 127(4), pp. 471-478.

[9] J. Mu, L. Zhang, and J. L. Rose, "Defect circumferential sizing by using long range ultrasonic guided wave focusing techniques in pipe," Nondestructive Testing and Evaluation,

Volume http://www.informaworld.com/smpp/title~content=t713645777~db=all~tab=issueslist~branches=22 - v2222, Issue 4, 2007, pages 239 - 253.
[10] J. Mu and J. L. Rose, “Long range pipe imaging with a guided wave focal scan,” Materials Evaluation, 2008, to appear.
[11] J. Mu, Guided wave propagation and focusing in viscoelastic multilayered hollow cylinders, Ph.D Thesis, The Pennsylvania State University, 2008.
[12] Ditri, J. J. and Rose, J. L., "Excitation of guided elastic wave modes in hollow cylinders by applied surface tractions," *J. Appl. Phys.*, **72**(7), 2589–2597, 1992.

One of the main applications of guided waves is for pipe inspection, since its one-dimensional geometry allows inspecting long distances in a short time. As with most configurations (frequency, thickness) ultrasonic waves with many modes of propagation are generated, recent research focuses mostly on the generation and reception of specific modes, mainly by means of sophisticated arrays of transducers. In this paper this problem is addressed with a different approach, by processing ultrasonic signals with a low signal/noise ratio acquired with a single transducer in an pulse-echo configuration Cylindrical guided waves are becoming popular for pipe inspection for their long distance propagation characteristics. For efficient use of cylindrical guided waves for pipe inspection, the wave propagation characteristics in cylinders should be understood. Gazis [1,2] first analytically solved the propagation of harmonic waves in an infinitely long elastic hollow cylinder. Greenspon [3,4] studied dispersion curves and displacement fields for an elastic cylindrical shell.Â 3. CONCLUSIONS Guided wave modes are shown to be strongly affected by the presence of holes in pipe walls. Although it is difficult to predict the hole diameter from the generated time history plots one can estimate it from the V(f) curves generated by taking the Fourier transform of the selected regions of the time history plots.