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Detection of Protective Coating Disbonds in Pipe Using Circumferential Guided Waves

Jason K. Van Velsor
Pennsylvania State University
Department of Engineering Science & Mechanics
212 Earth & Engineering Science Building
University Park, PA 16802, US
Tel: 00-1-814-8631852; Fax: 00-1-814-8638164
E-mail: jkv2@psu.edu

Joseph L. Rose
Pennsylvania State University
Dept. of Eng. Science & Mechanics
212 Earth & Eng. Science Bldg.
University Park, PA 16802, US
Tel: 00-1-814-8638026
Fax: 00-1-814-863-8164
E-mail: jlresm@engr.psu.edu

FBS, Inc.
143 Hawbaker Industrial Dr.
Suite 102
State College, PA 16803, US
Tel: 00-1-814-2343437
Fax: 00-1-814-2343457
E-mail: jrose@fbsworldwide.com

J. Bruce Nestleroth
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201, US
Tel: 00-1-614-4243181
Fax: 00-1-614-4583181
E-mail: nestlero@battelle.org

Abstract

Disbonded protective coatings greatly increase the corrosion rates in pipeline. A new guided-wave technology is developed for the detection of disbonds. Theoretical dispersion curves are generated for shear horizontal waves propagating around the circumference of a pipe. Three parameters are identified for the detection of disbonded coatings. Disbond detection is demonstrated experimentally using a 20" diameter pipe with a hot-applied coal-tar coating. Results show that there is potential for disbond sizing in addition to detection.

Keywords: Circumferential guided waves, Coating, Disbond, Pipe, SH-waves

1. Introduction

Until now, there has been no reliable means of detecting coating disbonds. Magnetic Flux Leakage (MFL) methods are commonly used for the detection of metal-loss corrosion but the technique requires that the material being inspected be ferrous. For this reason, it can not detect coating disbonds. Other coating integrity screening techniques, such as the Direct Current Voltage Gradient and Close Interval Potential Survey methods, are only capable of detecting coating faults if they are directly exposed to the soil.

The work summarized here introduces a new guided-wave technique for the detection of disbonded coating. The steady-state time-harmonic solution for circumferential Shear Horizontal (SH) guided waves propagating in a multi-layered hollow cylinder is discussed. Phase and group velocity dispersion curves and particle displacement profiles are presented for the case of a 20”-diameter pipe with a protective coating layer with properties similar to that of a hot-applied coal-tar wrap. Several features pertinent to the detection of disbonded coating are identified. Theoretical results are experimentally validated using SH-wave Electromagnetic Acoustic Transducers (EMATs) and a 20”-diameter pipe with a hot-applied coal-tar coating.

2. Theoretical Model

The dispersion equation for circumferential SH-waves in a single layer was presented by Zhao and Rose(1) and will be discussed in short here. The present authors have expanded this work to include *N*-layered structures. Other work on Lamb-type circumferential guided waves has been completed by Liu and Qu(2) and Rose(3).

Using an assumed harmonic solution, the solution to the governing equation, Navier’s equation, for SH-wave propagation in a hollow cylinder is given in terms of Bessel functions, as seen in Equation 1. The wave number, $k = \omega/c_p(r_{OR})$, is defined at the outer radius (OR) as the phase velocity is not constant through the thickness. The kr_{OR}-term is used in order to maintain constant phase through the wall thickness of the cylinder.

$$u_z = \left[A_1 J_{\hat{k}}(k_s r) + A_2 Y_{\hat{k}}(k_s r)\right] e^{i(\hat{k}\theta - \omega t)}, \quad r_{IR} \le r \le r_{OR}, \quad \text{where} \quad \hat{k} = kr_{OR} \quad \text{and} \quad k_s = \omega/c_s\,. \qquad [1]$$

For an *N*-layered structure, there will be an individual solution for each layer, resulting in *N* equations and *2N* unknown coefficients. In order to solve the dispersion equation and to determine the unknown coefficients A_1 through A_{2N}, the boundary and interfacial continuity conditions must be taken into consideration. At an interface between two layers, both displacement and shear stress are continuous. On a free surface, shear stress in required to vanish.

The Global Matrix Method (GMM) is used to solve the system of *N* equations. The underlying strategy of the GMM is to develop the displacement and stress equations for each individual layer and then, by applying the boundary and continuity conditions, it is possible to assemble a global matrix representing the entire layered system(4). The determinant of the global matrix results in the dispersion curves of the layered system. For SH-waves, the global matrix is *2N+1* square matrix.

Figures 1(a) and 1(b) show the phase and group velocity dispersion curves for a 20*in*-diameter schedule 10 pipe with a 3*mm*-thick coal-tar wrap coating, respectively. In Figure 1, the red lines are the dispersion curves for the coated pipe system and the black lines are the dispersion curves for a bare pipe and are shown as a reference. Table 1 shows the material properties and dimensions used for the generation of the dispersion curves.

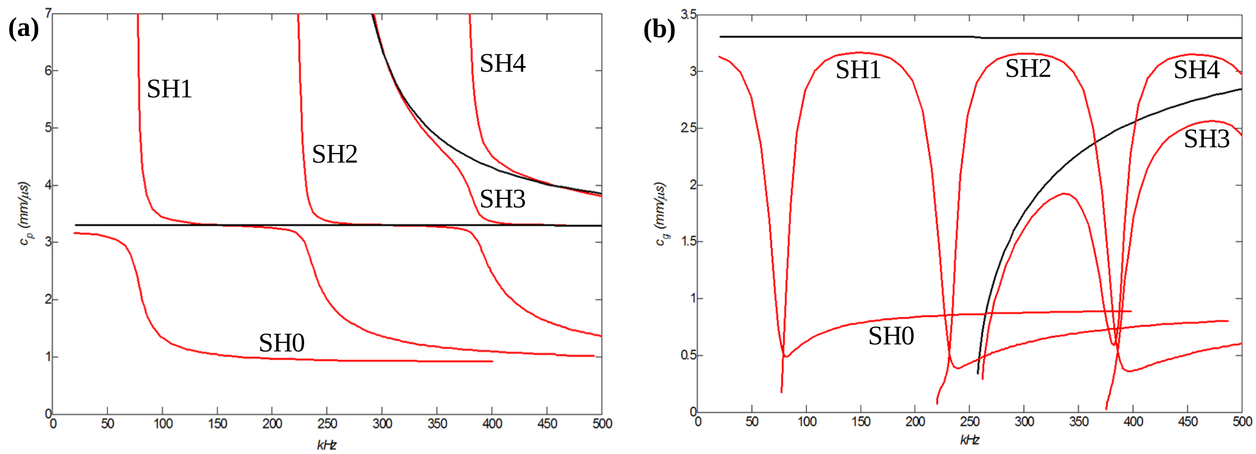

Figure 1: Phase (a) and group (b) velocity dispersion curves for a 20”-diameter schedule 10 pipe with a 3mm-thick coal-tar wrap coating. Black lines correspond to the bare pipe case and are shown for comparison.

Table 1: Material properties and dimensions used for dispersion curve generation.

	Layer 1	Layer 2
Inner Radius (m)	0.24765	0.254
Outer Radius (m)	0.254	0.257
Density (kg/m^3)	7930	1500
c_L (m/s)	5920	1400
c_S (m/s)	3260	900

Finally, with the roots of the dispersion equation known, it is possible to solve for the unknown coefficients, A_1 through A_{2N}, for any specific root. Example wave structures are shown in Figure 2 for several different roots of the dispersion equation. In Figure 2, the bottom layer corresponds to the pipe wall and the top layer corresponds to the coating material. Both displacement and shear stress are shown.

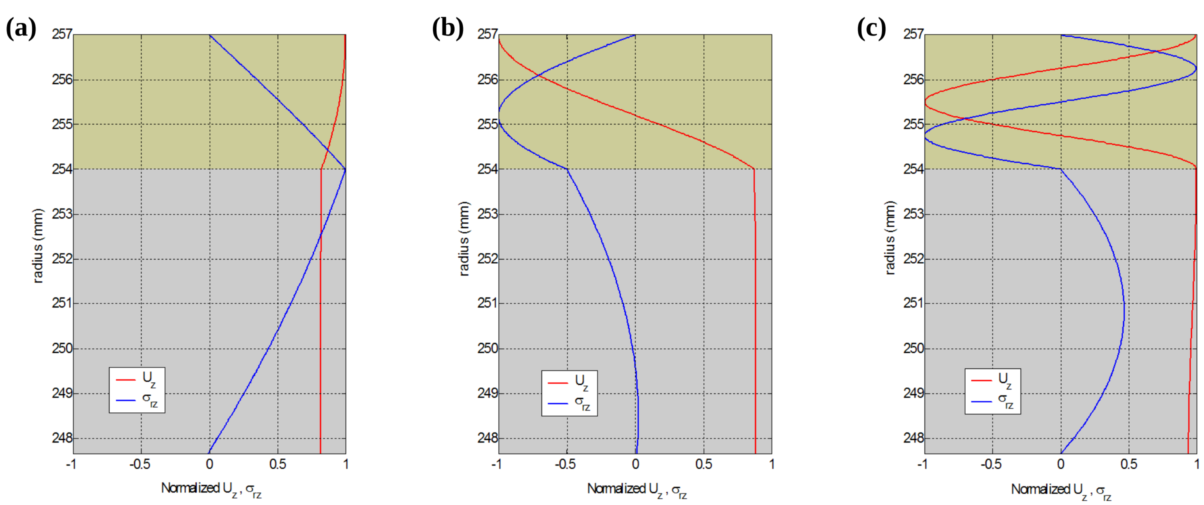

Figure 2: Particle displacement and shear stress distributions for (a) SH0 at 30kHz, (b) SH1 at 130kHz, and (c) SH2 at 312kHz.

3. Coating Disbond Detection

The theoretical model, developed in the previous section, can be used to determine wave propagation features that may potentially be sensitive to coating failures. Multiple detection features are necessary in order to create a robust and reliable disbond detection routine. Several potential features, including amplitude, time, and frequency-based features, are discussed next.

3.1 Amplitude-Based

Because of the attenuative nature of coating materials, disbonds will appear as an increase in received wave amplitude. This phenomenon can be seen in the ultrasonic guided-wave RF waveforms shown in Figure 3, which were collected on a 20”-diameter schedule 10 pipe with a 3*mm*-thick coal-tar wrap coating. Disbonds were created by removing the coating in specific areas. Data was collected using SH-wave EMATs with a designed wavelength of 24.85*mm*. For the structural geometry considered here, this sensor configuration generated the SH1 mode at a center frequency of 130*kHz*. The wave structure for this mode/frequency can be seen in plot (b) of Figure 2.

In order to use amplitude information reliably, a relative amplitude comparison is used in this study. All amplitudes are normalized to the “reference pulse” that travels directly from the transmitter to the receiver. The circumferential wave traveling in the CCW direction is the first wave to traverse the entire circumference and is therefore used for coating bond assessment. Table 2 summarizes the amplitude information seen in Figure 2. The blue dotted lines in Figure 4 indicate the amplitudes used in the calculations. It is seen that larger disbonds result in less amplitude loss and thus the first disbond detection feature is identified.

3.2 Time-Based

Consider the SH1 mode shown in Figure 1(b). This mode is relatively non-dispersive and has a noticeable velocity difference at a frequency of 130*kHz*. Additionally, the wave structure shown in Figure 2(b) indicates that there is both displacement and shear stress present at the coating interface. These are all desirable properties for time-based detection of coating disbonds. For this mode and frequency combination, the coated pipe case has a group velocity of 3.14$mm/\mu s$, as compared to a velocity in bare pipe of 3.30$mm/\mu s$. Therefore, disbonds will show as an overall decrease in the time-of-flight of a circumferential guided wave. The solid green lines shown in Figure 3 mark the peaks of the reference pulse and first CCW traversal of the circumferential guided wave. The time difference between these two marks is the time-of-flight for one complete circumferential traversal of the guided wave. The time-of-flight measurements for the three cases shown in Figure 3 are summarized in Table 2. As predicted, it is seen that there is an overall decrease in time-of-flight as the disbond size increases. This serves as a second, and much less obvious, disbond detection feature.

3.3 Frequency-Based

Because the coating layer is viscoelastic in nature, there will be some frequency-dependent attenuation due to absorption. In the case of guided SH-waves, attenuation increases with frequency. The absence of coating will facilitate higher frequencies. As the amount of well-bonded coating increases, higher frequency content will be filtered out by absorption. An experimental demonstration of this concept is shown in Figure 4, in which the Short-Time Fourier Transforms (STFTs) of the data sets displayed in Figure 3 are plotted. The ratio of the two white lines, marking the maximum frequency content of the reference pulse and the first CCW traversal, represents the amount of retained frequency content after one complete circumferential traversal of the pipe. The results are summarized in Table 2 and it is seen that as the disbond size increases, so to does the percentage of retained frequencies.

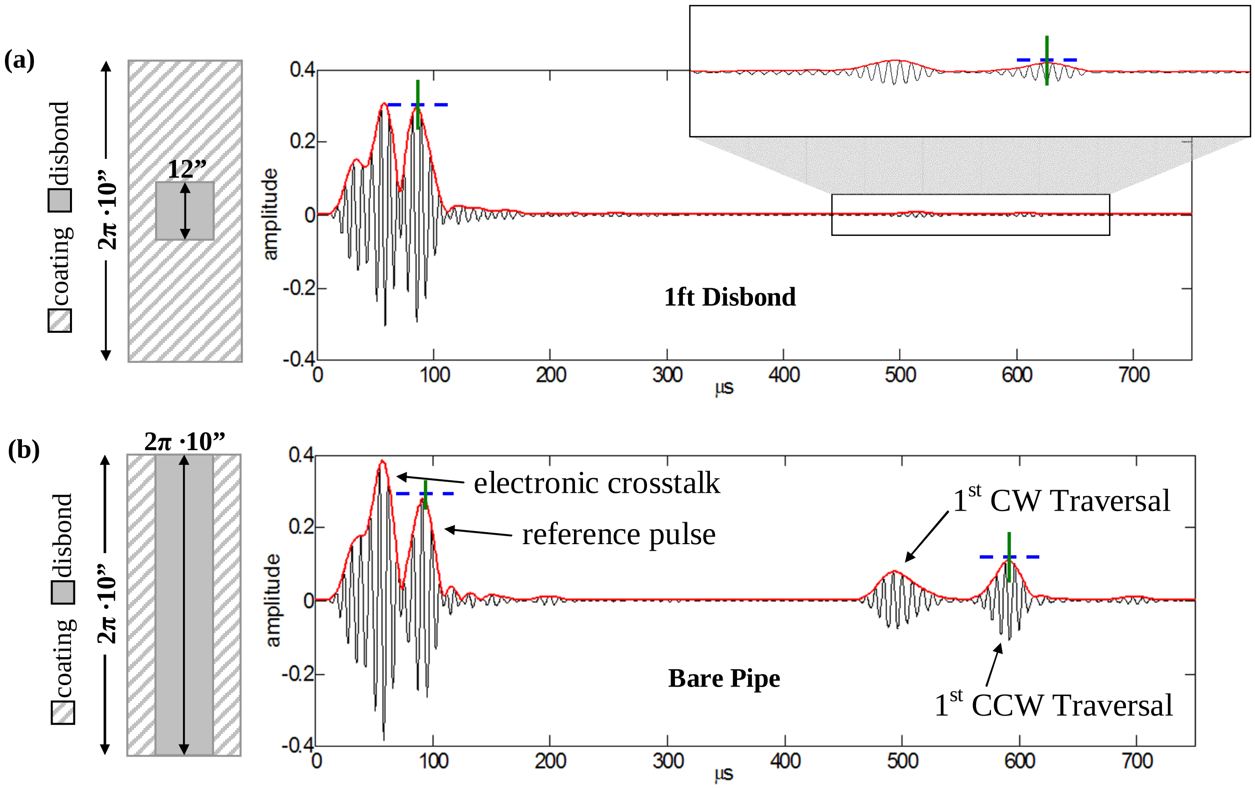

Figure 3: Ultrasonic waveforms obtained from a 20”-diameter schedule 10 pipe with a coal-tar wrap coating with a (a) 1ft. disbond and for a (b) bare pipe. The SH1 modes was used at a frequency of 130kHz.

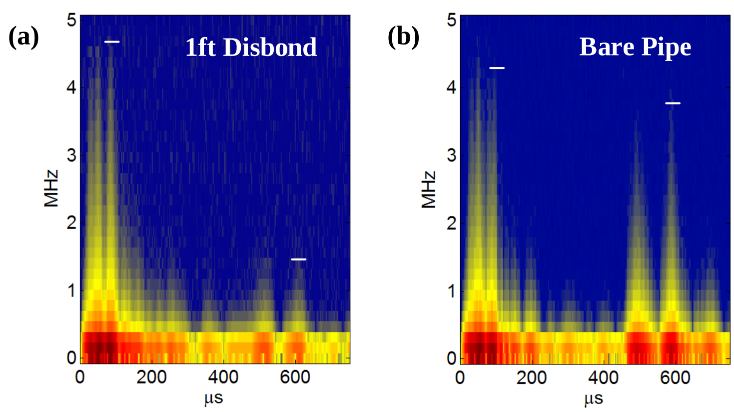

Figure 4: STFTs of RF-waveforms for a (a) 1ft disbond and a (b) bare pipe. A 64-point Hanning window with 32-point overlap was used.

Table 2: Amplitude, time, and frequency-based detection features for coating disbond detection. Though not shown in Figs. 3 or 4, data is included for a 2ft disbond.

	1ft Disbond	2ft Disbond	Bare Pipe
Amplitude Loss (dB)	35.14	30.87	8.19
Time-of-Flight (µs)	522.4	513.1	499.3
Retained Frequency Content (%)	31	50	90

4. Conclusion

A new guided-wave method for the detection of disbonds in protective pipe coatings was introduced. Theoretical modeling was used to select wave propagation features that were sensitive to coating disbonds. Amplitude, time, and frequency-based disbond detection features were introduced and the detection of disbonds in 20” diameter pipe with a coal-tar wrap coating was demonstrated experimentally with excellent results. In addition to detection, it is shown that there is excellent potential for disbond sizing.

Future work will involve the investigation of potentially confounding issues such as wetted interfaces and disbonds with soil compacted against the pipe. The SH mode group was chosen specifically because shear energy will not leak into viscous materials and should therefore have the highest probability of success in these types of environments. Other work will involve the study of the effects of defect presence on the coating disbond detection routine.

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