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Coating Disbond Detection in Pipe Using Circumferentially-Oriented Ultrasonic Guided Waves

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INTRODUCTION

The work summarized here specifically addresses the steady-state time-harmonic propagation of circumferential Shear Horizontal (SH) guided waves in a multi-layered hollow cylinder. The development of the dispersion equation for the single-layer case is discussed and then extended to the multi-layer case using the Global Matrix Method. Phase and group velocity dispersion curves 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.

THEORETICAL CONSIDERATIONS

The paper by Zhao and Rose(1) addressed the development of the dispersion equation for time-harmonic SH-wave propagation in a single-layer hollow cylinder. This work serves as a starting point for the work presented here. Other work on Lamb-type circumferential guided waves has been completed by Liu and Qu(2).

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 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. 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.

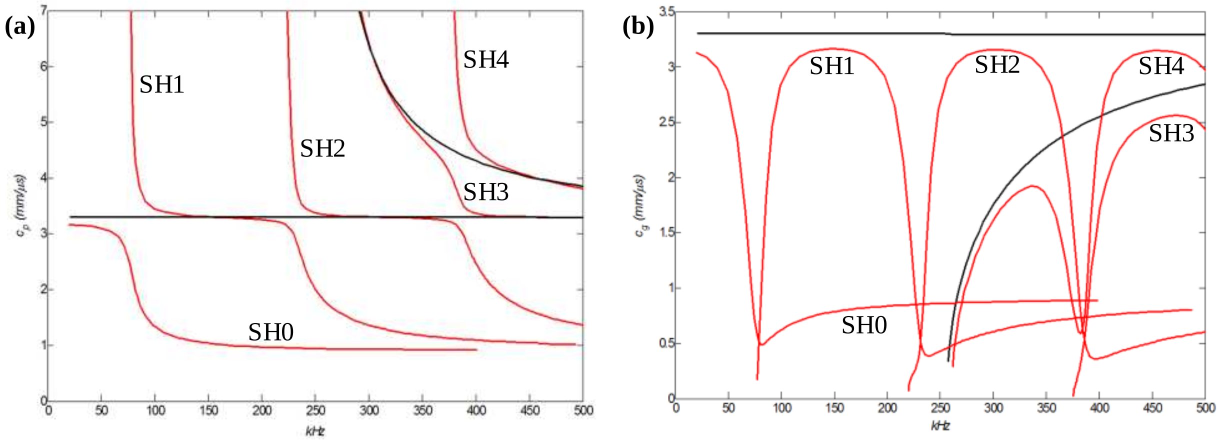

Figure 1: Phase (a) and group (b) velocity dispersion curves for a 20”-diameter schedule 10 pipe with a 3mm-thick coal-tar wrap coating. Black lines correspond to the bare pipe case and are shown for comparison.

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

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

COATING DISBOND DETECTION

The theoretical model 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.

Amplitude-Based

Disbonds will appear as an increase in wave amplitude of circumferentially traveling waves. This phenomenon can be seen in the ultrasonic guided-wave RF waveforms shown in Figure 2, which were collected on a 20”-diameter schedule 10 pipe with a 3*mm*-thick coal-tar wrap coating. Plot (a) corresponds to a 1’x1’ area of removed coating and plot (b) corresponds to a section of pipe with no coating. 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*.

Because amplitude is affected by many variables, a relative amplitude comparison is used in this study. The transmitting and receiving EMATs are separated by some short fixed distance and all amplitudes are normalized to the “reference pulse” that travels directly from the transmitter to the receiver. For the experimental setup used in this study, 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 ratios between the first CCW traversal and the reference pulse for the two coating conditions shown in Figure 2. The blue dotted lines in Figure 2 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.

Time-Based

As shown in the group velocity dispersion curves, Figure 1(b), there is a noticeable decrease in the maximum velocity at which a group of waves can propagate in a coated pipe as compared to the case of a bare pipe. This velocity difference between the bare pipe and coated pipe cases can be used as a disbond detection feature.

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*. 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$mm/\mu s$. The solid green lines shown in Figure 2 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 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.

Frequency-Based

The tendency of attenuation to increase with frequency can be used as a coating disbond detection feature. The absence of coating will result in a frequency spectrum with higher frequency content. 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 3, in which the Short-Time Fourier Transforms (STFTs) of the data sets displayed in Figure 2 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.

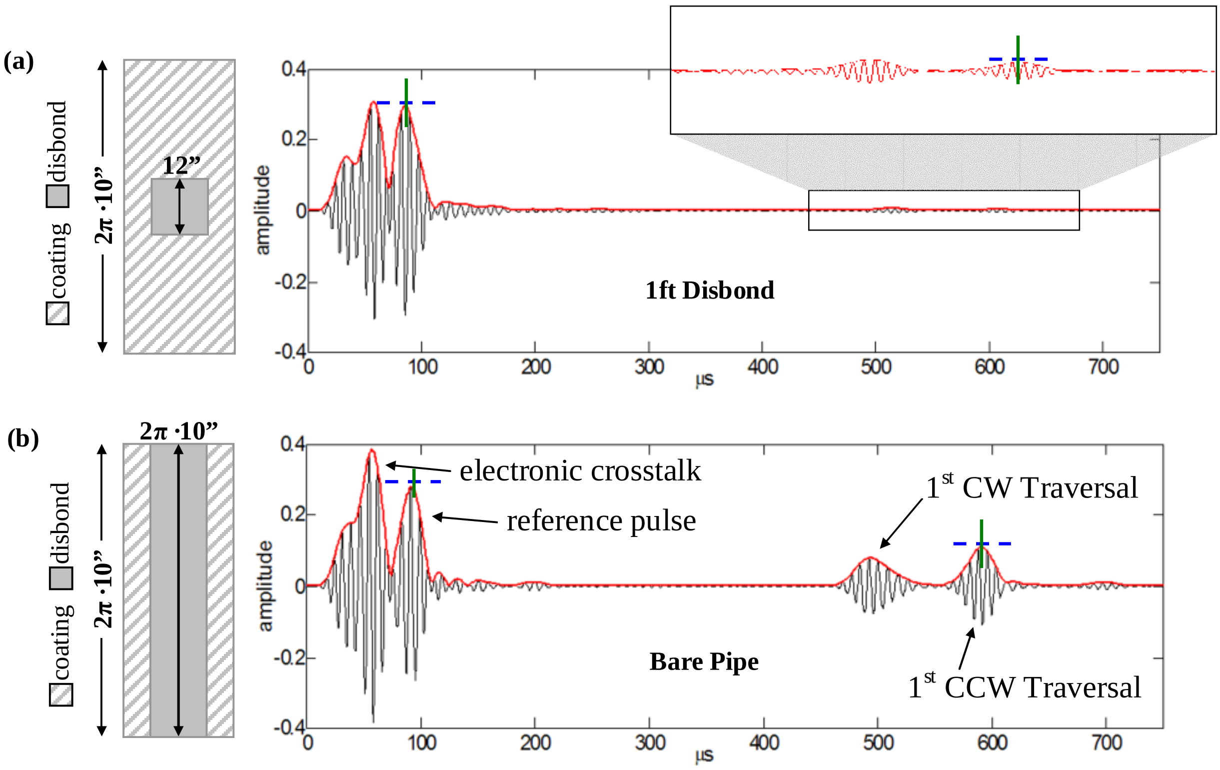

Figure 2: Ultrasonic waveforms obtained from a 20”-diameter schedule 10 pipe with a coal-tar wrap coating with a (a) 1ft. disbond and for a (c) bare pipe. The SH1 modes was used at a frequency of 130kHz.

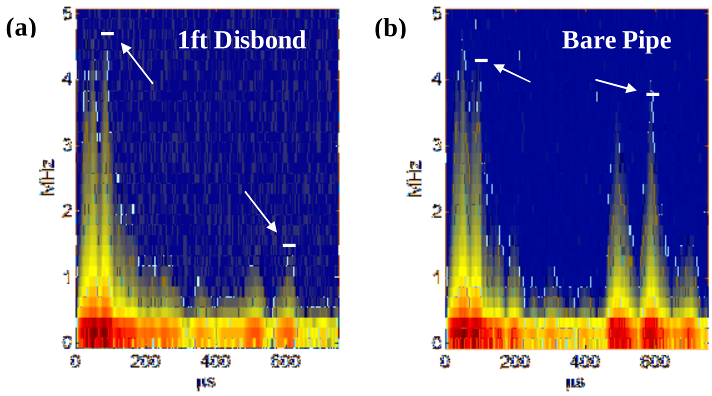

Figure 3: STFTs of RF-waveforms for a (a) 1ft disbond and a (b) bare pipe. A 64-point Hanning window with 32-point overlap was used.

Table 2: Amplitude, time, and frequency-based detection features for coating disbond detection.

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

CONCLUSION

A multi-layer theoretical model for circumferentially propagating SH-waves has been developed using the Global Matrix Method. Sample dispersion curves and wave structures were shown for a 20”-diameter schedule 10 pipe with a 3*mm*-thick coal-tar wrap coating. Three wave propagation features relevant to the detection of disbonded coating were identified. These features were based in the amplitude, time, and frequency domains. It was shown experimentally that coating disbonds result in an increase in received wave amplitude, a decrease in time-of-flight, and in a larger retained frequency spectrum. While all three of these features were individually shown to successfully detect coating disbonds, it is the integration of these features that will result in a robust and reliable guided-wave disbond detection routine. Other potential disbond detection features include the presence of reflections from the disbond boundaries, dispersivity of a particular mode/frequency, and a plethora of inter- and intra-mode velocity, dispersivity, amplitude, and frequency content comparisons.

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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