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Guided Wave Thickness Measurement Tomography for Structural Health Monitoring in Critical Zones of Pipelines

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Abstract

Structural health monitoring is becoming an increasingly important field as the amount of infrastructure across the globe increases and as older structures deteriorate. A significant portion of this infrastructure is represented by oil and gas pipelines. Such pipelines are exposed to harsh conditions like corrosion and abrasive wear. Ultrasonic bulk wave measurements of critical zones in steel pipe implemented by conventional means have proven to be time-consuming and dangerous to personnel. Some pipes carrying high pressure have been known to rupture upon inspection, injuring or killing inspection personnel. Permanently placed ultrasonic transducers mounted in an array around a critical zone on a pipeline can be used to monitor wall thinning and other damage types safely and quickly via ultrasonic tomographic reconstruction of the pipeline structure. There are many conceivable uses for which such a sensor would prove advantageous. A few of these uses includes locations that are difficult to access such as underground pipelines or areas of high congestion, regions requiring high sensitivity, geometrical discontinuities like diameter reductions and pipe bends, and pipelines carrying high pressures which are dangerous to test using conventional methods. Also, this sensor can potentially be integrated with wireless capabilities and become even more safe and convenient to use, as personnel near the sensor to perform inspections will not be necessary.

Keywords: Ultrasonic guided waves, pipes, structural health monitoring

1. Introduction

Much work has been done in developing methods in non-destructive evaluation and testing over the past years. The most useful current methods include the use of high energy (x-ray and radiology), magnetic flux leakage, visual, audio, and ultrasonic techniques. Up until recently, most work in ultrasonic methods has focused on the use of bulk waves to detect damages and anomalies such as cracks, voids, delaminations, and other material degradations. This type of analysis provides a straightforward means for examining structures for these types of defects.

In addition to bulk waves, more recent research has focused on using ultrasonic guided waves in NDE and SHM applications. A good deal of contemporary work has been done using guided wave tomography [1-5]. Guided waves have several distinct advantages over bulk waves. These advantages include: infinite numbers of wave modes which can be selected and optimized for a specific use in testing, the ability to inspect structures over long distances, and lower access requirements [6]. The more powerful of these attributes for use in thickness measurements is the ability of guided waves to give information about a structure over some distance, as opposed to bulk waves offering only information about the local structural properties.

Ultrasonic tomography is a very powerful technique for monitoring many types of structures. Ultrasonic tomography employs an array of ultrasonic sensors around some region of interest on a waveguide. Signals are collected between each pair of sensors. Changes in these signals from one session of data collection and another signify changes in the waveguide. An example of a tomograph obtained on a pipe elbow is shown in Figure 1. This tomogram was taken on a steel pipe elbow of 7 mm wall thickness. The damage represented in this tomogram is of 0.23 mm wall thinning. Red regions of the plot indicate the damage. More details on this can be found in [4].

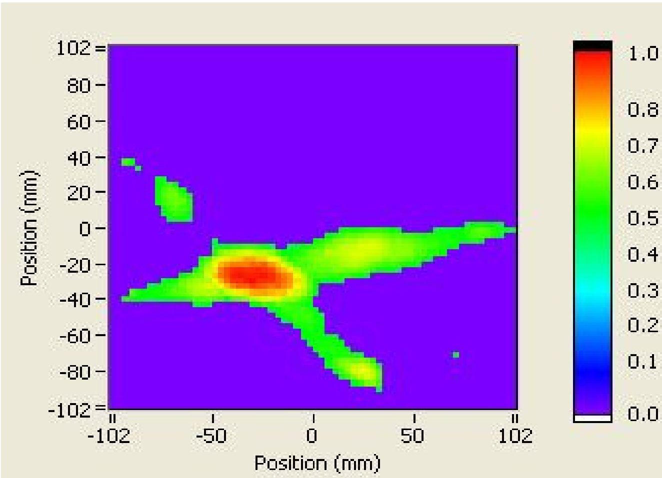

Figure 1. Tomogram taken using a 16-sensor array on a steel pipe elbow. See [4] for more details.

This technique can be employed on structures that are not possible to access for bulk wave measurements due to spatial restrictions from other portions of the structure, and for areas that pose significant risk to human inspectors. It is of interest to develop feature-based components for the interpretation of data collected via these tomograms. This is of particular interest in understanding the next fundamental step in ultrasonic tomography. Current tomography is very useful for noting changes, even very small changes of any type in a waveguide, but so far the wave mechanics involved have not been fully explored. It is desirable to be able to use certain features of a propagating mode between each sensor pair in a tomographic array to study signature waveforms from specific damage types such as wall thinning or cracks. This work will focus on the thickness measurement of isotropic plates and plate-like structures of uniform thickness. Note that pipelines of large diameters with respect to their thickness can be approximated as plate-like structures.

2. Theoretical Development

Guided waves will only propagate in a structure for particular combinations of phase velocity and frequency. For plates, these values will be given by the roots of the Rayleigh Lamb equations. These equations are not developed here but are given by Rose in [6]. These equations are

$$\frac{\tan(qh)}{q} = \frac{4k^2 p \tan(ph)}{\left(q^2 - k^2\right)^2} \quad (1)$$

for symmetric lamb modes,

and

$$q \tan(qh) = \frac{\left(q^2 - k^2\right)^2 \tan(ph)}{4k^2 p} \quad (2)$$

for anti-symmetric modes where

$$p = \sqrt{\frac{\omega^2}{c_L{}^2} - k^2} \quad (3)$$

and

$$q = \sqrt{\frac{\omega^2}{c_t{}^2} - k^2} \quad (4)$$

ω here is the angular frequency, k is the wave number, c_l is the bulk longitudinal wave velocity, and c_t is the bulk shear velocity. The lowercase h denotes the plate thickness. A plot of the roots of equations (1) and (2) as a function of phase velocity and frequency results in the dispersion curves for the waveguide of interest. An example of this representation is given in Figure 2. This figure represents the phase velocity dispersion curves for a steel plate of 1 mm thickness. Due to the dependence of the product of frequency * thickness (f*t product), in the arguments of equations (1) and (2), a particular mode will exist at unique values of the f*t product. Thus, the curves in Figure 2 would shift toward the right if the thickness of the plate were reduced, and toward the left if the plate were thicker.

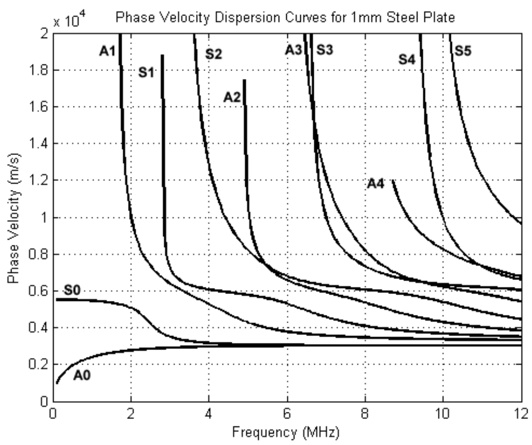

Figure 2. Phase velocity dispersion curves
for a 1 mm steel plate.

By selecting a particular phase velocity for use in exciting energy into a structure, the dispersion curves predict those frequencies that will support propagating modes in the waveguide. For the steel plate example shown in figure 2, a propagating mode should exist with 10 km/s phase velocity at a frequency of 2 MHz (the A1 mode). A different mode (S1) will exist for the same phase velocity at roughly 2.9 MHz. Thus, by sweeping across many frequencies with a loading that generates wave modes of a particular constant phase velocity, it is possible to obtain a thickness measurement of the structure based on the frequencies that produce propagating wave modes. For these frequencies, the amplitude of the resulting RF signal collected between a transmitter and receiver will have much higher amplitudes relative to the same signal obtained for frequencies and phase velocity combinations that do not coexist with propagating modes on the dispersion curves. A plot of the maximum RF signal amplitude as a function of frequency will then show amplitude peaks wherever the frequency is appropriate to excite propagating modes at the phase velocity being used.

For Non-destructive testing, the number of peaks occurring in a signal can be used to estimate the thickness of the waveguide under investigation. As can be noted from Figure 2, a frequency sweep of particular bandwidth will cover a certain number of mode crossings at a given waveguide thickness. If the thickness of the plate used in Figure 2 were thicker, more mode crossings would appear in the same frequency window shown (0 to 12 MHz), and fewer if the thickness were less. While the number of peaks appearing in this type of frequency sweep will not necessarily be unique to a single waveguide thickness, it will be unique to a small range of possible waveguide thicknesses.

In Structural Health Monitoring, the number of peaks obtained as discussed previously can be used along with their frequency locations relative to a laboratory reference or some other reference to measure the deviation in thickness in the waveguide relative to the reference signal. Again, as indicated in equations (1) and (2), the f*t product will be constant for the reference signal and a signal obtained in SHM. Thus, if the frequency of the peaks changes, the thickness change responsible for this change can be calculated by adjusting the thickness "t" part of the f*t product to produce the same value as found in the reference signal. This procedure can be followed for many transducer locations around some region of interest on the waveguide to construct guided wave thickness measurement tomography on a structure.

3. Experimental Validation

The thickness difference between two stainless steel plates of different thicknesses was measured using the frequency sweeping method discussed in the theoretical development section. For this experiment, a stainless steel specimen of 6.038 mm was obtained. A section of this specimen was machined to a thickness of 4.848 mm (80 percent of the original thickness), and another section was kept at the original thickness. A set of broad-banded transducers were used in through transmission in a frequency sweep as outlined before. The frequency range of this sweep was from 100 kHz to 6 MHz. The center frequency of the transducers was 5 MHz. The transducers were located at a distance of 80 mm from each other and were oriented to produce normal loading. Maximum amplitudes were taken of each RF signal collected in this sweep. Figure 3 shows the maximum amplitude of each RF signal as a function of frequency for the 6.038 mm plate. Superimposed on this plot are results obtained in the same fashion for the 4.848 mm plate.

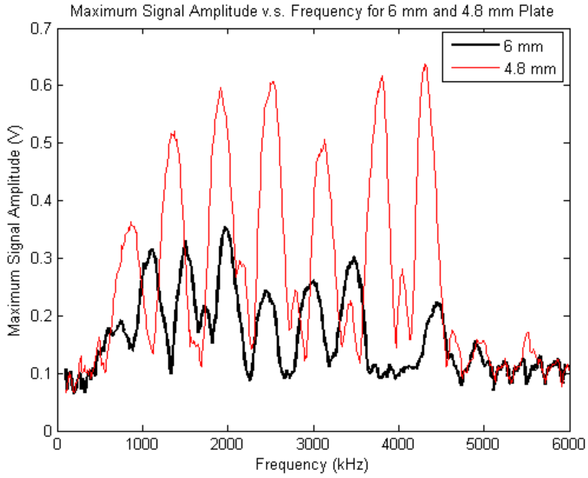

Figure 3. Maximum RF amplitude as a function of frequency for two stainless steel plates of different uniform thicknesses.

It can be seen that there are more peaks for the thicker (black curves) plate. Also, note that the frequencies of each local maximum for the thinner plate (red curves) are shifted somewhat toward the right from those of thicker portion of the specimen. The measured peak frequencies of these waveforms are tabulated in Table 1. It is shown in this table that the frequency shift of almost all the peaks in these plots indicate the correct difference in thickness between the two specimen sections. The first set of peaks shows an unusually large error in this measurement, but this is probably due to these peaks corresponding to waves with different phase velocities than the modes for the other frequency peaks. The other peaks show a deviation of 2 percent or less from the actual thickness difference between the two plates.

Table 1. Frequencies of Peak Amplitude

6.038 mm Plate	4.848 mm Plate	
Measured Frequency (kHz)	Measured Frequency (kHz)	Shift Ratio (%)
750	860	87
1100	1360	81
1500	1900	79
1970	2520	78
2450	3100	79
3000	3800	79
3470	4300	81

4450		

4. Conclusions

A technique for measuring the thickness of a plate-like waveguide of uniform thickness using guided waves had been demonstrated. A pair of transducers was used in through transmission to collect RF signals resulting from a frequency sweep on stainless steel plates of different thicknesses. The thickness difference between the plates was 80 percent. The locations of maximum RF amplitude in the frequency spectrum of each plate were used to measure the difference in thickness between the two plates. This technique demonstrated an accuracy of about 2 percent in identifying the thickness difference between the two plates. This method can be used in ultrasonic tomography as a feature based analysis of the waveguide of interest.

6. References

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