

# Guided Wave Helical Ultrasound Tomography of Pipes and Tubes

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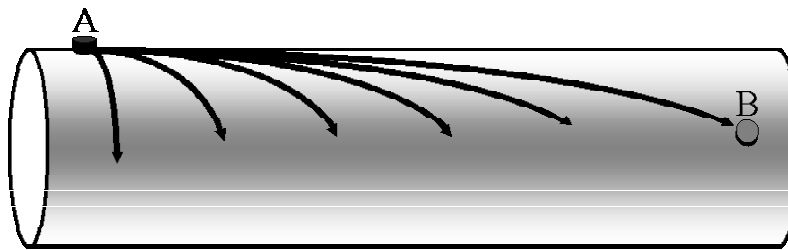
Guided ultrasonic waves have many useful properties that can be exploited for inspecting large-area structures such as aircraft skins, storage tanks and piping systems. First and foremost, they can be made to propagate significant distances in either pitch-catch or pulse-echo configurations, accumulating information about the structure all along the propagation path. Of particular interest to pipe inspection, they follow the curvature of the structure and can be directed along any desired helical path from circumferential to longitudinal. Moreover, as the guided waves propagate, they involve the entire thickness of the pipe wall in a complex elastic deformation and recovery so that they are sensitive to flaws on the inner diameter, outer diameter and in between, i.e. under coatings. They can be launched and received by externally mounted transducer belts, internal pigs, and by a wide variety of contact and non-contact transducer configurations.

The blessing and curse of guided ultrasonic waves is their inherent complexity. An infinite number of modes are available for use, each with characteristic dispersion and through-thickness displacement properties. At low frequencies longitudinal, torsional and flexural pipe modes dominate, but at higher frequencies these structural modes are less important and the waves see the pipe more and more as a curved plate or shell. It is these helical guided wave modes that are of interest in our measurements. We find that these modes can be made to behave similarly to Lamb wave modes in plates, and that helical criss-cross paths are a useful tomographic geometry equivalent to what seismologists use in their cross-borehole tomography. Tomographic reconstruction is key because it allows the complexity of the guided wave modes to be harnessed, resulting in a readily interpretable “map” of the structural flaws of interest. For example, if one selects a mode with high sensitivity to thickness variations, i.e. it speeds up or slows down when the pipe wall thickness changes, then by noting deviations from the expected arrival times of the many criss-cross helical paths the tomographic reconstruction is easily rendered as a wall-thickness map. For many pipe inspection applications, such accurate mapping out of wall thickness changes is a primary concern. With appropriate software expert systems to identify and sort out the features of interest from the received guided wave modes, the entire measurement process can be automated so that the inspector needs to have mastered none of the complexity of guided wave ultrasonics.

## **Description of Guided Waves and Tomography**

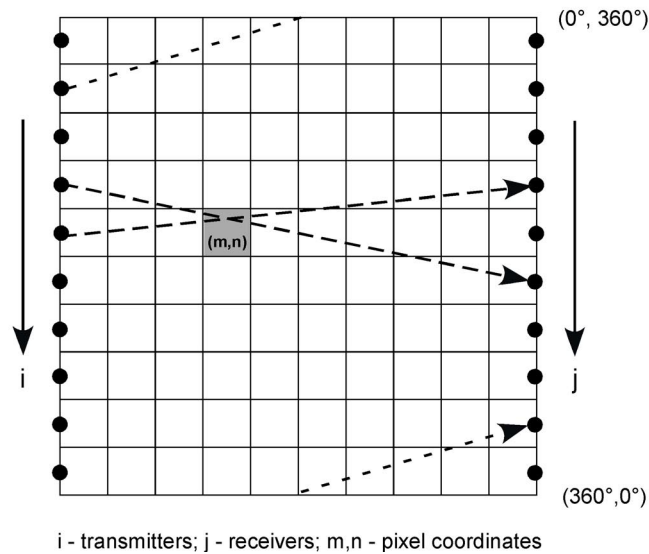
Elastic waves in extended solids are either longitudinal or transverse, characterized by compressional or shear vibrations, respectively. Boundaries cause mode coupling and inter-mixing of these waves to the extent that it's no longer useful to try to distinguish between them. Locally plate-like structures have two boundaries and we refer to the intermixed propagating compressional and longitudinal vibrations as Lamb waves [1]-[2]. Lamb waves come in two families of modes, usually termed symmetric and anti-symmetric. The lowest-order symmetric mode is a thickness bulging and contracting while the lowest-order anti-symmetric mode is a constant-thickness flexing, with higher-order modes having increasingly complex through-thickness displacements. Curved plates behave similarly except that for pipe-like objects (where the plate curves around upon itself) some additional complexities arise. The first one is that the pipe as a whole can exhibit three families of propagating modes: torsional, flexural and extensional [3]-[5]. These can be distinct from, or intermingled with Lamb wave (plate) modes in the pipe. Generally speaking we can hope to distinguish pipe modes from plate modes in that the former are lower in frequency and longer in range while the latter are higher frequency more localized phenomena. Of course there's no clear demarcation between the two regimes and in practice it's necessary to be able to sort them out or the unwanted modes will corrupt the data sets of interest. A second complexity that

arises for pipe-like objects is that more than one helical mode can travel between any two transmit and receive locations. In Figure 1 we show a pair of transducers on a pipe segment, and several helical rays propagating away from the transmitting transducer, one of which takes the most direct path part way around the pipe to the receiving transducer. Others with steeper helicities will travel further around the pipe circumferentially and will miss the receiver. Still others will make one or more complete loops around the pipe and end up at the receiver. Although one could envision “aiming” the waves in a narrow enough beam to avoid this confusion, tomographic considerations require that both the transmitting and receiving transducers be as omni-directional as possible. This adds yet a third complexity which is that the helical waves are generated in both clockwise and counter-clockwise and depending on the relative angular positions of the transmitting and receiving transducers these pairs of modes may interfere either constructively or destructively.



**Figure 1.** A pipe segment is shown with a transmitting transducer at *A* and a receiving transducer at *B*. Six helical Lamb wave paths are shown, with the shallowest only just beginning to wrap around the pipe before it reaches *B*. The steepest possible helical path is the circumferential guided wave that will ring around the pipe and be received at *A*. In between these two extremes the guided wave modes are launched at *A* for all helicities (4 are shown) some of which will travel around the pipe one, two and more times before being recorded at *B*. Note also by symmetry that all of these waves go in the opposite directions as well, and these mirror modes will, in general, overlap with the guided wave modes of interest at the receiver *B*. Sophisticated software to almost instantaneously sort out and identify all of these various modes in thousands of jumbled waveform is key to making the HUT technique work.

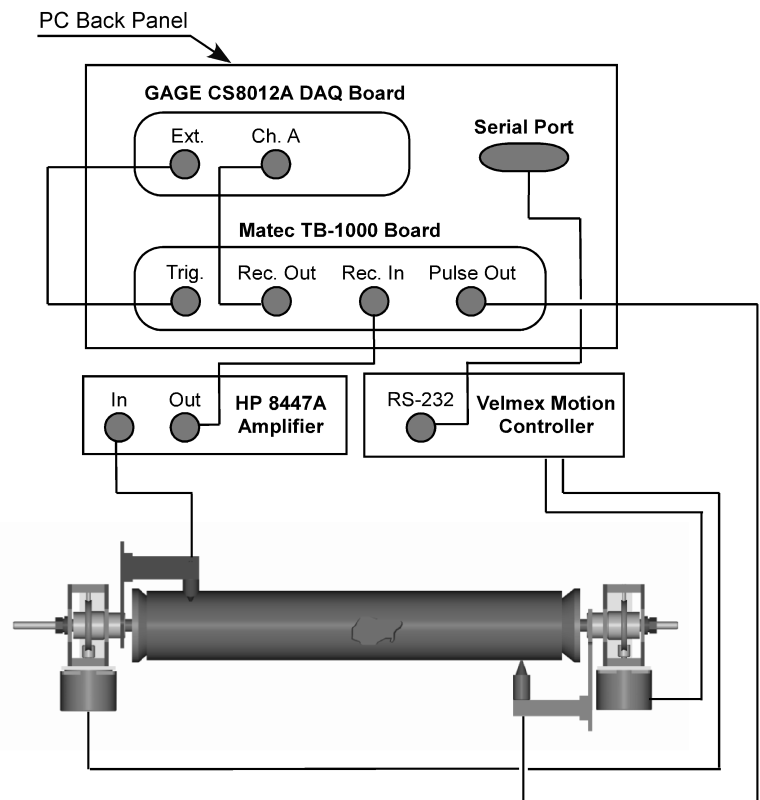
Of course all of this complexity is what one faces in the *absence* of any flaws. Flaws scatter and refract the guided waves, and even cause energy to be converted from one mode to another. These effects can be severe for strongly scattering flaws such as cracks. Thickness changes due to gouging can cause some modes to be cut off, resulting in a fairly dramatic reflection of those same modes or a dumping of the wave energy into other modes. In our previous work on Lamb wave tomography in plates we have developed some techniques to handle much of this complexity, and have now found that we are able to deal satisfactorily with the added difficulties of pipe-like geometries. If we envision a series of pitch-catch helical guided wave measurement on a pipe or tube with a large number of transducers along two separated circumferential belts, the set of helical criss-cross ray paths is a tomographic geometry. In Figure 2 we illustrate this by showing a surface-grid which is “unwrapped” and laid flat. The transducers now lie along parallel lines in what seismologists call a crosshole geometry [6] making a criss-cross ray pattern. Because the helical waves can wrap around the pipe more than once we can consider the “extra” regions and the longer ray paths to give better tomographic reconstruction because these rays pass through the region of interest from additional angles.



**Figure 2.** An unwrapped tomographic grid is shown with filled circles indicating ten transmitters on the left and ten receivers on the right. Three different ray paths are shown with by the dashed arrows. Note that for this geometry  $0^\circ$  and  $360^\circ$  are the same physical location which is indicated by the ray that exits the grid at top center and enters the grid at bottom center.

In order to perform the tomographic reconstructions we have assembled the apparatus shown in Figure 3. It mimics the two circumferential belts of transducers via a pair of transducers incremented by stepper motors under computer control. For each transmitter location a guided wave is launched by exciting the transducer with a toneburst while the receiver is paused briefly at all of the circumferential positions. The frequency of the toneburst is chosen to select the guided wave modes of interest, typically those that will be first arriving so as to minimize complications from overlapping modes. The recorded waveforms at each pitch-catch pair location are digitized and processed on the computer to extract the arrival time(s) and/or amplitude(s) of the mode(s) of interest. Additional projections are taken by stepping the transmitter to all of the circumferential positions and repeating the process. The complete set of arrival times or amplitudes are then passed to the tomographic reconstruction codes.

**Figure 3.** The computer-controlled scanner steps the two transducers through all the necessary pitch-catch positions to mimic a pair of circumferential belts of transducers. A narrow-frequency toneburst signal is generated in order to minimize the number of Lamb-wave modes present. The RF waveforms are digitized and processed in software to identify the modes of interest and track subtle changes in them due to the presence of flaws. Features extracted from the waveforms are then passed to the tomographic reconstruction algorithms, which run on the same PC that controls the measurements.



We have found in our previous work [7]-[15] that the iterative families of algorithms developed in the seismological literature are better suited to our purposes than are the convolution-backprojection algorithms developed for medical imaging and other applications. In particular, we find that the simultaneous iterative reconstruction tomography (SIRT) algorithms are relatively robust, computationally efficient, and insensitive to experimental noise. They also have the inherent advantage of being widely applicable to a variety of geometries and incomplete data sets. Moreover, we have been able to adapt and extend these algorithms to account for material anisotropy and “ray bending” due to scattering from flaws.

We have recently begun working in collaboration with Nascent Technology Solutions, LLC ([www.nascentnde.com](http://www.nascentnde.com)) to optimize the HUT technique for artillery gun barrel inspection for the US Army in order to provide a reliable technique to assess condition and remaining service life of operational and future combat systems. The prototype system being built under that project uses two transducer array belts to replace the scanner described here and provide a simple-to-use strap-on system.

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