# Appendix A: Interactive Wavelet Thumbprint Tool for Guided Wave Ultrasound Signals

**Overview**

Because fingerprints are useful for identifying people, it is natural to propose a signal "fingerprint" for classifying signals. The basic question is how to define such a fingerprint. For ultrasound applications, we are mostly concerned with the local or transient properties of the signals. Specifically, we need to locate the center of the transient signal first and then we need a suitable window to isolate the transient signal from its neighborhood. Finally, we need to use a suitable method to extract significant information to distinguish one transient signal from another. With excellent time-frequency localization properties, the wavelet transform is a suitable tool for all these requirements.

To form a wavelet fingerprint, we project several slices of the continuous wavelet transform of the isolated pulse onto the time-scale plane, which results in a two-dimensional black and white image (Fig. A1). Once we have obtained the 2-D signature of the transient signal, we can convert the one-dimensional signal classification problem to a two-dimensional pattern problem in order to make use of more advanced tools at our disposal.

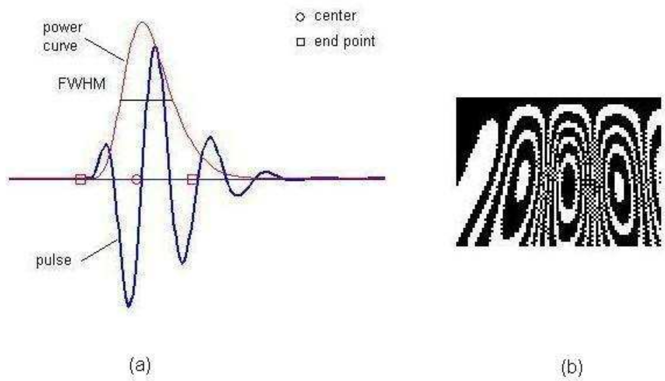
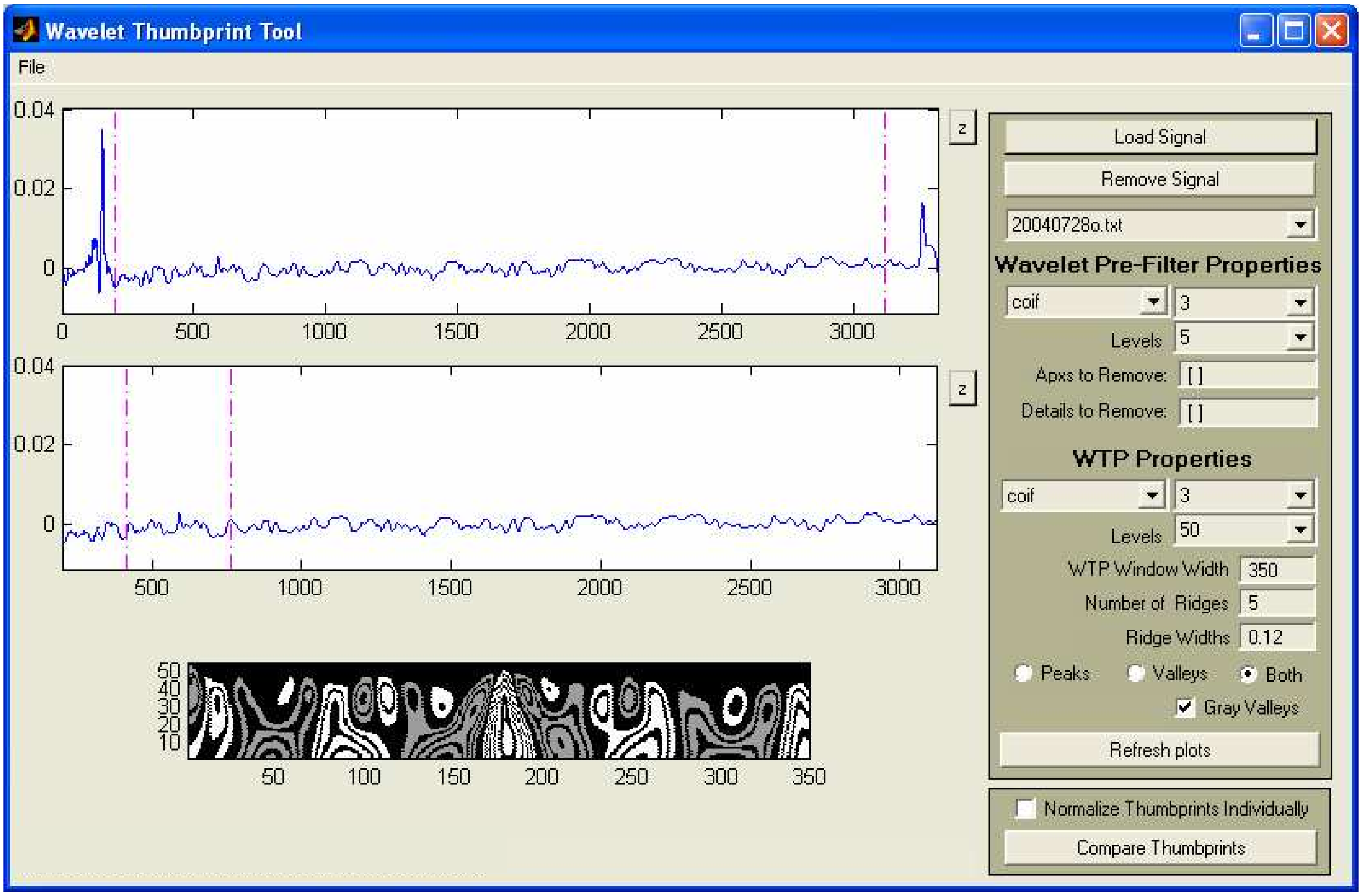



**Fig.A1.** Ultrasound pulse (a) and its dynamic wavelet fingerprint (b).

The Wavelet Thumbprint Tool (WTPtool) described below provides a simple and interactive user interface that can be used to create and view Wavelet Thumbprints for pitch-catch guided wave ultrasound signals (A-SCANS) in order to recognize characteristic patterns associated with piping flaws.

## To Run the Wavelet Thumbprint Tool

The Wavelet Thumbprint Tool requires a current version of MATLAB with the Wavelet Toolbox. To run the Wavelet Thumbprint Tool, enter "wf" in the MATLAB command window.



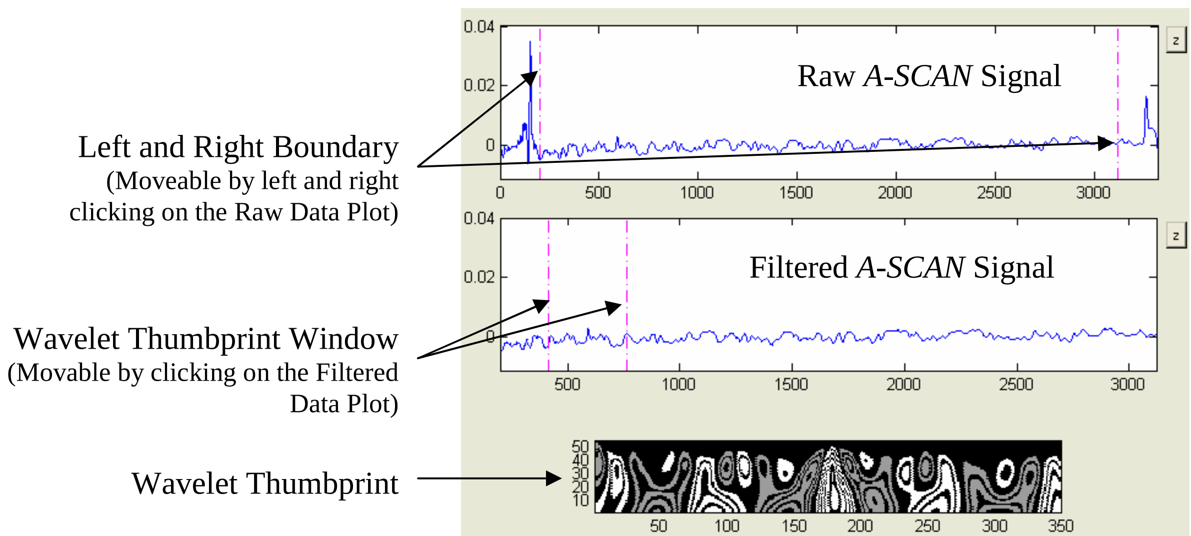

## Loading and Viewing signals

A-SCAN signals (waveforms) are loaded using the "Load Signal" button. More than one signal can be loaded during a single session. The pop-down menu located below the "Remove Signal" button can be used to select a signal to be viewed. When pressed, the "Remove Signal" button will remove the current signal. Once a signal is loaded, you will see three plots on the left hand side of the window. An example is shown below.

*Raw A-SCAN Signal*
The top plot displays the raw *A-SCAN* signal. The purple lines represent the left and right cropping boundaries. These can be set by clicking the left and right mouse button.

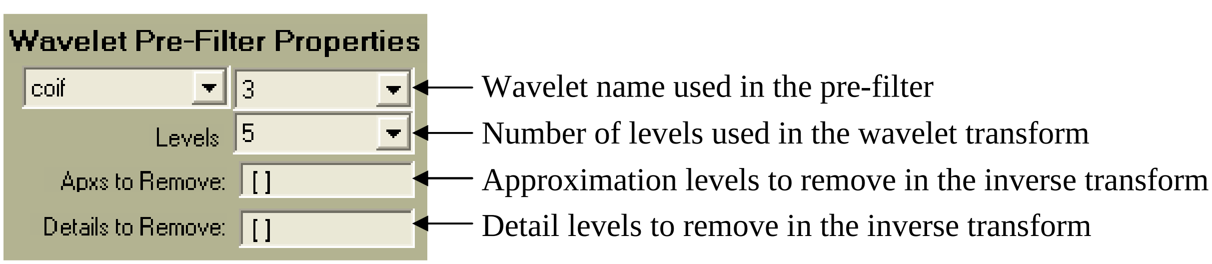
*Filtered A-SCAN Signal*
The second plot displays the filtered A-SCAN signal. The data is filtered according to the Wavelet Pre-filter (denoise) properties on the right hand side of the window. The purple lines on this plot indicate the section of the filtered data that will be used in making the Wavelet Thumbprint. This Wavelet Thumbprint window can be moved by clicking on the plot or using the left and right arrow keys.

*Wavelet Thumbprint of the A-SCAN Signal*
The last plot displays the Wavelet Thumbprint that is created according to the Wavelet Thumbprint (WTP) properties on the right hand side of the window. Right clicking on this plot or the filtered data plot will place a red reference line on both plots. This can be used to indicate which two-dimensional features in the Wavelet Thumbprint correspond to the one-dimensional features in the *A-SCAN* signal.



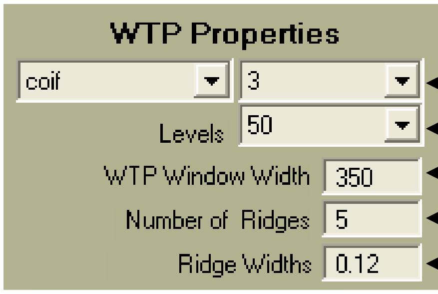

## Wavelet Pre-Filter Properties

A Wavelet Pre-Filter is performed on the raw signal using a discrete stationary wavelet transform. This separates the signal into its details (high scales) and its approximations (low scales). These parts can then be individually removed from the signal. The default settings do not remove any approximation or detail levels. For example, if you wanted to remove the first three levels of the details (commonly used to denoise a signal), then the appropriate entry in the "Details to Remove:" field would be "[1 2 3]" or "[1:3]".



**Wavelet Thumbprint (WTP) Properties**

The Wavelet Thumbprint is created by taking a continuous wavelet transform of the filtered signal. The coefficients of the wavelet transform are then represented as a set of ridges that resemble fingerprints.




← Wavelet name used in the continuous wavelet transform
← Number of levels used in the wavelet transform
← Width of the Wavelet Thumbprint window
← Number of ridges used to create the Wavelet Thumbprint
← Width of the ridges (Normalized to 1)

**Different Views of the Wavelet Thumbprint**

Selection buttons are provided to display only the peaks (positive values), the valleys (negative values), or both peaks and valleys of the Wavelet Thumbprint. When both peaks and valleys are displayed, the “Gray Valleys” option will shade the valleys in gray so that they are distinguishable from the peaks.


← View selection buttons
← Option to gray the valleys (negative values) of the WTP
← Refresh the plots using the current settings

**Compare Thumbprints**

The Compare Thumbprint button will display Wavelet Thumbprints for all of the loaded signals using the current settings. The thumbprints are displayed from top to bottom in the same order as they were loaded and appear in the pop-down menu.

The Normalize Thumbprints Individually option will normalize each signal separately before the thumbprints are created.

**Background on this technique**

For a wide variety of NDE applications, we have found time-domain signal processing to be relatively inaccurate compared to 2D techniques. In particular, we favor joint time-frequency and time-scale transforms which convert the 1D time trace echoes into 2D representations. The best-known example of this family of techniques is the “spectrogram” which computes an FFT inside a sliding window to get a 2D plot which shows both the frequency content of the reflection and how that changes over time. The goal is to find the optimal time frequency kernel for the particular signals of interest (it’s almost never the spectrogram) so that artifacts are minimized while features of interest are enhanced.  Similarly, a wavelet transform can be constructed from a variety of mother wavelets to give a scale vs. time 2D representation. One can then do a 2D version of template matching or cross correlation to compare one or many of these 2D parameter images with those stored in a library. Alternatively, one can collapse these 2D parameter images back down to 1D traces in a variety of ways and then perform template matching, etc. with them. Although visualizing an “error surface” becomes problematic in the now higher-dimensional representation, there is no inherent limit on the number of dimensions to be used. In addition to the offset-shift and smoothing parameters, there are a variety of parameters (e.g. the spectrogram window length) that may be of use.

Recently we’ve implemented a Dynamic Wavelet Finger Print (DWFP) algorithm to interpret echoes from an ultrasonographic periodontal probe, extract multi-mode waveform properties from a guided wave tomography system, and identify deeply-buried delaminations in microchip packaging via acoustic microscopy. We found that time-domain processing was not accurate enough for these purposes, but by performing a continuous wavelet transform on the A-lines and then a simple contouring operation on the resulting 2D data maps we obtain 2D black and white images that look remarkably like fingerprints. Comparing binary (black and white) images to templates allows us to draw on optical character recognition technology, of course, but our real goal is to make use of the extensive fingerprint classification systems that were developed in the early $20^{th}$ Century. Although these systems eventually became unwieldy due to the inability to cross check larger and larger databases by hand, they did result in a variety of classification schemes that may be simple to utilize now. These schemes turned fingerprint images into strings of numbers and letters which could be written down on a card and carried, or sent via letter or telegraph. We should also note that fingerprint (and facial) identification technology is currently advancing rapidly, with some of the most successful algorithms operating by identifying the relative coordinates of characteristic features rather than by comparing one image to another. Spatial relationships of features in the 3D and higher dimensions of the *A-SCAN* data may be quite useful for interpreting the *A-SCAN* data.

**Selected References:**


First paper on wavelet fingerprint for materials sorting:

- *Dynamic Wavelet Fingerprint Identification of Ultrasound Signals* (M. Hinders, J. Hou) Materials Evaluation **60**, #9 1089-1093, (2002).

Various papers on the ultrasonographic periodontal probe, which uses the wavelet fingerprint:

- *Ultrasonic Device for Measuring Periodontal Attachment Levels* (M. Hinders, J. Lynch) Reviews of Scientific Instruments, **73,** #7, 2686-2693 (2002).
- *Clinical Tests of an Ultrasonic Periodontal Probe* (M. Hinders, J. Lynch, and G. McCombs) in "Reviews of Progress in Quantitative Nondestructive Evaluation Vol. 21", D.O. Thompson and D.E. Chimenti, eds. AIP CP 615, 1880-1887 (2002).
- *Ultrasonic Periodontal Probing Based on the Dynamic Wavelet Fingerprint* (M. Hinders, J. Hou and S.T. Rose) J. Applied Signal Processing, Vol. 2005, No. 7, 1137-1146 (2005).
- *Clinical Comparison of an Ultrasonographic Periodontal Probe to Manual and Controlled-Force Probing* (M. Hinders, J. Lynch and G. McCombs) Vol. 35, #5, Measurement (2006).
- *Ultrasound Technology: Emerging Applications for Dentistry in Periodontal Assessment* (M. Hinders, G. McCombs) April cover story, Dimensions of Dental Hygiene (2006).

Various papers on Lamb wave tomography, which uses the wavelet fingerprint:

- *Comparison of Double Crosshole and Fanbeam Lamb Wave Tomography*, (M. Hinders, E. Malyarenko), in "Reviews of Progress in Quantitative Nondestructive Evaluation", Vol. 20, D.O. Thompson and D.E. Chimenti, 732-739 (2001).
- *Lamb Wave Tomography for Monitoring Aircraft Structural Integrity,* (M. Hinders, E. Malyarenko and J. Heyman), in USAF Aircraft Structural Integrity Program Conference Proceedings, 2001.
- *Blind Test of Lamb Wave Diffraction Tomography* (M. Hinders, E. Malyarenko and K. Leonard) in "Reviews of Progress in Quantitative Nondestructive Evaluation Vol. 21", D.O. Thompson and D.E. Chimenti, eds. AIP CP 615, 278-283 (2002).
- *Ultrasonic Lamb Wave Tomography* (M. Hinders, K Leonard and E. Malyarenko) Inverse Problems Special NDE Issue, **18,** #6, 1795-1808 (2002).
- *Guided Wave Helical Ultrasonic Tomography of Pipes,* (M. Hinders, K. Leonard) JASA, Vol 114, #2 767-774 (2003).
- *Lamb Wave Helical Ultrasonic Tomography of Pipes* (M. Hinders, K. Leonard) in "Reviews of Progress in Quantitative Nondestructive Evaluation Vol. 23", D.O. Thompson and D.E. Chimenti, eds. 173-179 (2004).
- *Automatic Multi-mode Lamb Wave Arrival Time Extraction for Improved Tomographic Reconstruction* (M. Hinders, J. Hou, Kevin R. Leonard) Inverse Problems **20**, 1873-1888 (2004).
- *Lamb Wave Tomography of Pipes and Tanks using Frequency Compounding* (M. Hinders, Kevin R. Leonard) in "Reviews of Progress in Quantitative Nondestructive Evaluation Vol. 24", D.O. Thompson and D.E. Chimenti, eds. 867-874 (2005).
- *Multi-mode Lamb Wave Arrival Time Extraction for Improved Tomographic Reconstruction* (M. Hinders, J. Hou, Kevin R. Leonard) in "Reviews of Progress in Quantitative Nondestructive Evaluation Vol. 24" D.O. Thompson and D.E. Chimenti, eds. 736-743 (2005).
- *Multi-mode Lamb Wave Tomography with Arrival Time Sorting* (M. Hinders, Kevin R. Leonard) JASA, Vol. 117, #4, 2028-2038 (2005).
- *Lamb wave tomography of pipe-like structures* (M. Hinders, K. Leonard) Ultrasonics, Vol. 44, #7, 574-583 (2005).

Acoustic microcscopy for inspecting microchips using the wavelet fingerprint:

- *Ultrasonic Inspection of Thin Multilayers* (M. Hinders, J. Hou, J.C.P. McKeon) in “Reviews of Progress in Quantitative Nondestructive Evaluation Vol. 24”, D.O. Thompson and D.E. Chimenti, eds. 1137-1144 (2005).

Time-Domain Reflectometry (TDR) paper using the wavelet fingerprint:

- *Wavelet Thumbprint Analysis of Time Domain Reflectometry Signals for Wiring Flaw Detection* (M. Hinders, J. Bingham, K. Rudd, R. Jones and K. Leonard) in “Reviews of Progress in Quantitative Nondestructive Evaluation Vol. 25”, D.O. Thompson and D.E. Chimenti, eds. pp. 641-648 (2006).