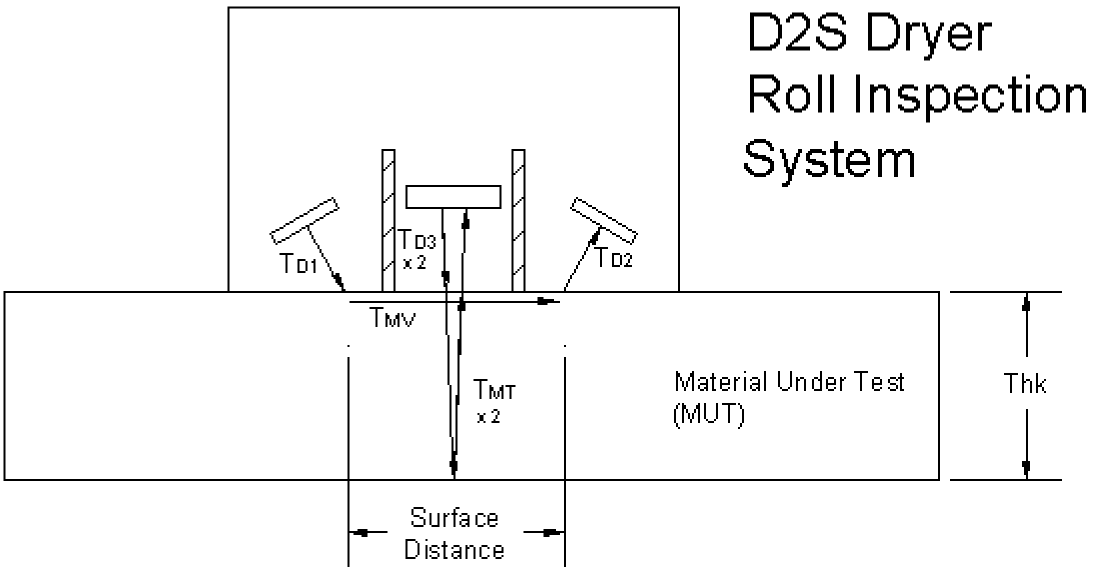
D2S System

"Wedge" Principle



The complexity in doing ultrasonic inspection on cast iron paper machine dryer rolls arises from the fact that the velocity of sound travel in the material is not constant as it is in normal isotropic materials such as carbon steel. This means that you can not calibrate on a thickness step block and then test the material with the assumption that it will be the same. Normal thickness calibration adjusts for two variable parameters: the probe delay, or time that it takes for the sound to travel in the transducer assembly itself, and the velocity, which is the distance of travel you can assume you have measured given a certain measured elapsed time of sound travel in the material itself.

The ultrasonic instrument physically measures the time of sound travel. It can convert this to a thickness using the velocity setting in the scope parameters. The equation for determining thickness using a known velocity and elapsed time of travel (time-of-flight) is:

Thickness = (velocity x elapsed time) / 2

Velocity is in the units inches per microsecond

The actual value of velocity x elapsed time is divided by two because you are measuring the time after the sound pulse has to travel to the back wall of the material and then back to the transducer. The probe delay is not shown in the above equation because it is assumed that the "zero offset" setting (should equal actual probe delay) has been subtracted to measure only the time traveled in the material itself.

NOTE: the proper parameter to set for probe delay in most digital instruments is "ZERO OFFSET". The "DELAY" parameter relates to screen placement and should be left at 0.

Given two known thickness values, you can "scale" the instrument directly on isotropic materials by making the time scale on the screen relate directly to the known thicknesses. On anisotropic materials like cast iron, the velocity can change in different areas of the material. The "wedge" principle is used to measure the velocity at any point and then use this to calculate the thickness.

The wedge principle works by measuring the time of flight of a longitudinal surface wave across a known distance. This is what the velocity signal shows. This measured time of flight can be used to calculate the velocity in the material if the distance is known and the time of flight in the probe is subtracted (probe delay). The known distance and the probe delays vary in every wedge, since it is very difficult to produce wedges that are identical. The D2S system measures and accounts for the probe delays in each set of transducers, as well as the known surface distance, using a special four-step calibration. This makes it superior to previous systems that make assumptions on wedge construction or use correction factors in the UT instrument. This means that if you calibrate before every inspection set-up, any quality wedge is interchangeable with the instrument, which may not be true with other systems.

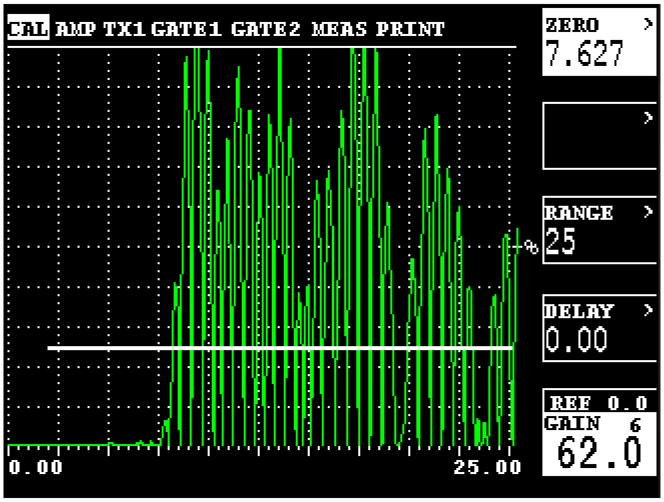
An additional factor must be accounted. Since the travel of the sound from the transmitting thickness transducer element to the receiving element is not directly perpendicular, a correction factor must account for the actual "V path" of the sound travel. In the D2S system, this factor is not calculated in the scope or computer, which may cause interchangeability and speed problems. The factor is accounted for by direct measurement over the thickness calibration range and included in the velocity stamped on the calibration blocks. This means that the velocity stamped on the blocks is not the actual velocity, but includes a correction factor for the "V-path". Actual velocity is not needed by the system, and the stamped velocity should not be used for transducers other than the "wedge".

You will notice that the D2S system does not immediately measure the thickness. The UT instrument is set up to measure time of flight using microsecond units rather than inches. The system measures time-of-flight and velocity at each measurement interval using a solid-state two channel multiplexer (the instrument displays the thickness signal at the instrument repetition rate between intervals). These values are plotted vs. each increment position on two strip charts (b-scan type displays) simultaneously in real-time. This allows you to judge the individual qualities of the two signals before thickness conversion. The thickness conversion is performed using a tool button in the analysis mode of the *Analyst* software. This also allows you to "clip" and interpolate bad velocity data before the conversion. It should also be noted that the thickness cannot be calculated using the time of flight (microseconds) <u>of the instrument display</u> and a known or measured velocity. This is because the probe delays are different between the two sets of transducers, and the instrument screen is set for the shortest of the delays. The D2S program subtracts the extra delay of the other set from the measured screen value in real time.

It should be noted that some physical limitations exist in the "wedge" technique. Some of these include effects such as "frequency diffraction", the finite size of the sound beam vs an infinitely small point source, the trigonometric relationship of the "V-path" and geometric variance, and gain sensitivity in the thickness measurement. The D2S system approaches the tradeoffs with an effort to reduce complexity and errors as much as is feasible and possible. The system is set up to reliably measure shell thickness in varying field conditions, and is not biased to the calibration blocks.

THICKNESS AND VELOCITY WAVEFORMS

The D2S wedge transducer has a frequency of 1 Mhz and the UT instrument is automatically set to this frequency by the software communication. Higher frequencies are less sensitive to gain in the thickness measurement due to the steeper leading edge of the signal (vs gate threshold), but they attenuate in the cast material. The software automatically switches to the velocity transducer pair at each measurement interval during an actual scan after recording the thickness pair time-of flight at that interval. For waveform evaluation while calibrating, etc., clicking on the Thickness/Velocity tool button will switch from one channel to the other. This button is available in one screen of the calibration wizard, and is also available under the Display Options menu (Multiplex Pair button). Below are typical waveforms for the thickness pair on each step of the calibration blocks at a typical gain.



ZERO 7.627

RANGE 25

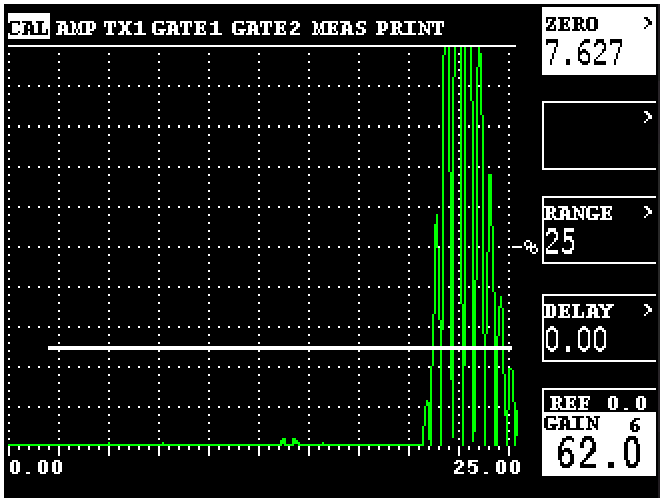
DELAY 0.00

REF 0.0

GAIN 6

62.0

Fig 2



ZERO 7.627

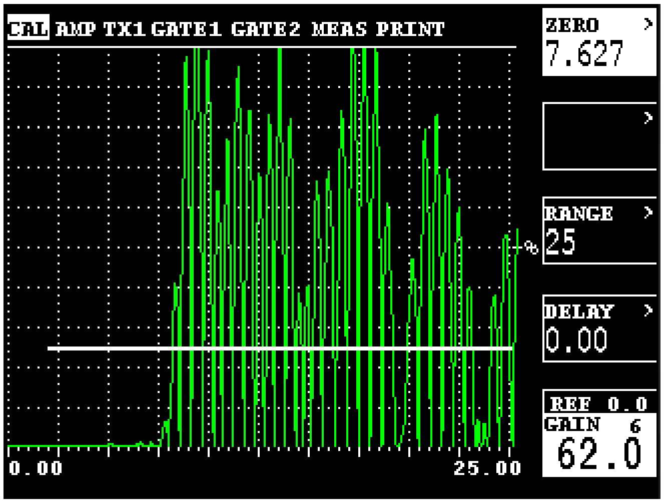
RANGE 25

DELAY 0.00

REF 0.0

GAIN 6 62.0

Fig 3



ZERO 7.627

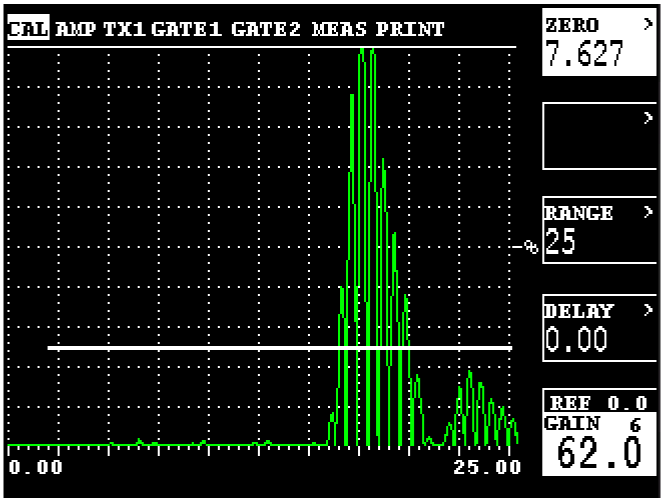
RANGE 25

DELAY 0.00

REF 0.0

GAIN 6 62.0

Fig 4



ZERO 7.627

RANGE 25

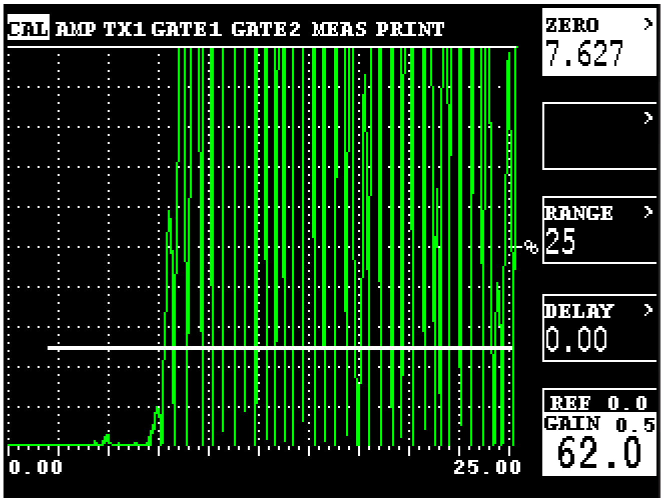
DELAY 0.00

REF 0.0

GAIN 6 62.0

Fig 5

The velocity waveforms on each material at a typical gain are shown below.



ZERO 7.627

RANGE 25

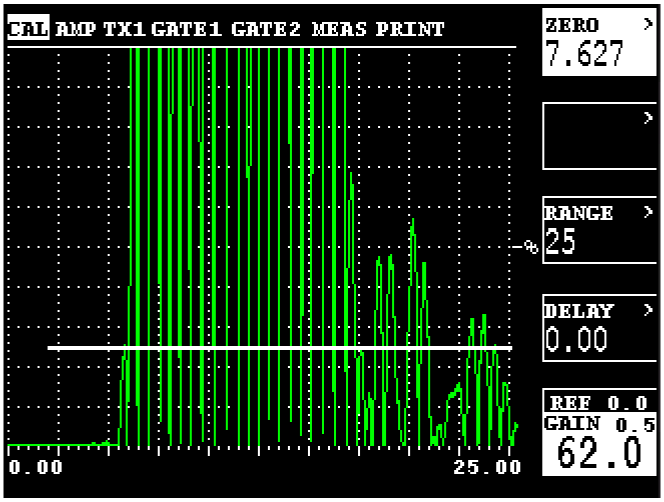
DELAY 0.00

REF 0.0

GAIN 0.5

62.0

Fig 6



ZERO 7.627

RANGE 25

DELAY 0.00

REF 0.0

GAIN 0.5

62.0

Fig 7

Fig's 6 & 7 show the first half cycle lobe of the surface velocity signal. It is very important to monitor this to reduce what we call "half cycle error". This is what we mean when we say that the measurement is gain dependent. If the first lobe is above the gate level, the measurement will record to the point where this lobe crosses the gate. If it is just below the gate, the instrument will record the end of the measurement where the next lobe crosses the gate. The D2S system sets the UT instrument to full wave rectification. This essentially flips all of the negative cycles above the baseline (0 voltage level) so that all half cycles are pointed upward from the baseline. To see an example of what the actual RF (radio frequency) waveform from the transducer looks like, set the instrument temporarily to "RF" using the "DETECT" menu setting under the "AMP" menu. At a 1 Mhz frequency, one cycle is 1 microsecond in length. Remembering that a full cycle includes the upward swing from the baseline, the downward swing and then back to the baseline where the next cycle starts, a half cycle is 0.5 microseconds long. Looking at Fig 6, the time measurement is about 3.15 divisions out of 10 times the screen range of 25 microseconds or:

(3.15 / 10) x 25 = 7.85 microseconds

On this transducer, the velocity pair probe delay is less than the thickness pair (this is almost always true on these wedges), so the absolute time measurement on the screen (7.627) is correct for the velocity pair. If you look at the next half cycle over, it is about 0.2 major divisions further in time, and equates to:

(0.2 / 10) x 25 = 0.5 microseconds

which confirms our calculation based on transducer frequency. Catching a different half cycle results in an error of:

0.5 / 7.85 = 0.0637 or 6%.

Near the peak of the first cycle the gate will catch the cycle further toward the middle vs the side of the next cycle, so the actual error is usually less.

This gain dependent error can also occur on the thickness measurements. On a material with a velocity of 0.1800, the difference between two half cycles equates to about:

(0.1800 inches / microsecond x 0.5 microseconds) / 2 = 0.045 inches

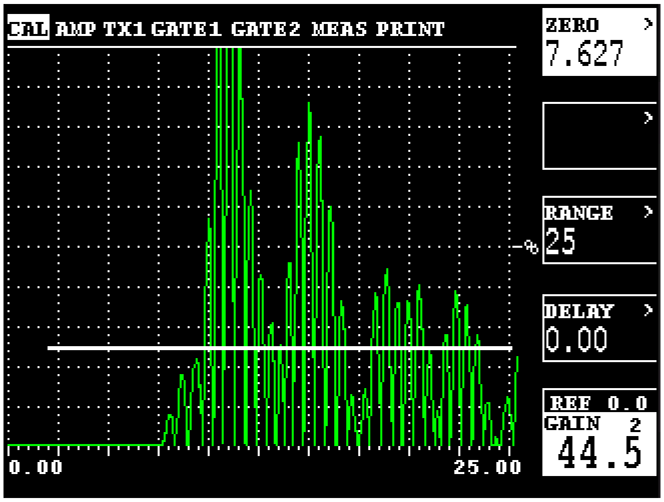
which is about 4.5% error on a 1 inch thickness. Since the sound on this pair travels to the back wall and back to the transducer, the error gets effectively reduced by a factor of 2 since it is only a one-way error on a there-and-back measurement. This is where the divide-by-two factor comes from in the above equation.

Fortunately, these errors are not directly additive. As a matter of fact, they partially cancel each other most of the time, so you will seldom see errors as large as either of the above. For example, if you catch a later half cycle on the velocity pair, it will make the velocity reading at that spot read low or as if it were slower. A low gain will likely also read the thickness a half cycle late, or like it took longer to travel that distance. The example below assumes that the half cycle error on each pair is 0.5 microseconds.

(0.1763 inches / microsecond x 5.67 microseconds) / 2 = 0.500 inches
(0.1657 inches / microsecond x 6.17 microseconds) / 2 = 0.511 inches.

Note that the surface distance on the wedge in use determines the amount of velocity change from a 0.5 microsecond error. The exact error also depends on the waveform due to the material, gain and coupling of one pair versus the other, etc. A review of the waveforms above reveals that the relative heights of the first lobes on each transducer pair may vary with material.

Another important factor in this inspection is using the correct gain and gating on the correct signal. On the velocity pair of transducers, you have a longitudinal mode wave traveling along the surface, but since this requires a certain angle of incidence other than perpendicular, a shear wave is also generated. Other reflections, refracted waves, and mode converted signals may also be present, depending on the part geometry. The longitudinal surface wave will actually be lower in amplitude than many of these signals, so it is possible to trigger the gate on the wrong signal if the gain is too low. The main point to remember is that the longitudinal surface wave that you are seeking will get to the receiving transducer before any other signal echoes since it is traveling a shortest distance, so it will be the first signal to the left. Other wavefronts may overlap the trailing edge of the signal of interest. This is demonstrated in Fig. 8 below, where the gain is set too low to trigger on the surface wave, which includes the first three lobes to the left. The high amplitude signal being gated is not the signal of interest for velocity determination. Fig. 9 shows the signal on the thick section of the brass calibration block, where most of the other signals are not present. The first signal on the left is the longitudinal surface wave at too low of a gain to trigger the gate. Fig. 10 shows both of these signals superimposed on each other, with the Fig. 9 signal in red, and demonstrates more clearly where the longitudinal surface wave is at the leading edge of the Fig. 8 signal. Fig. 11 shows the two velocity waveforms at same two locations at a proper gain, which is 62 db in this case. (Fig.'s 10 & 11 do not show gate or parameters).



ZERO 7.627

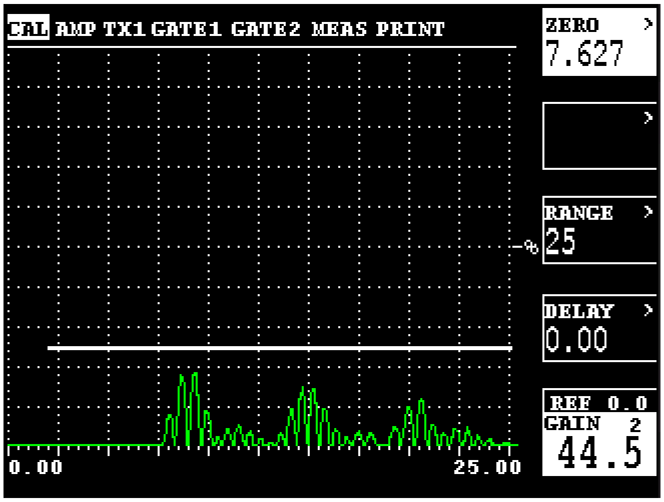
RANGE 25

DELAY 0.00

REF 0.0

GAIN 2 44.5

Fig 8



ZERO 7.627

RANGE 25

DELAY 0.00

REF 0.0

GAIN 2 44.5

Fig 9

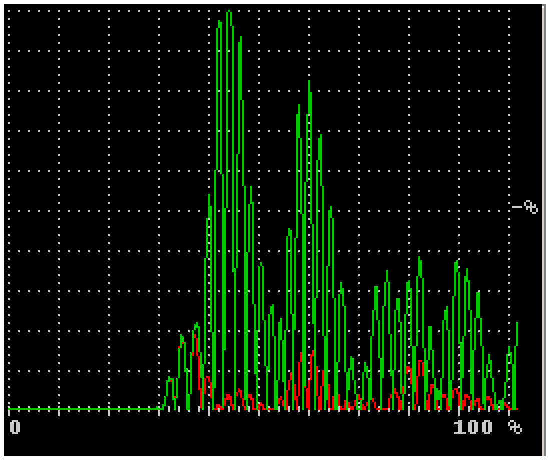


Fig 10

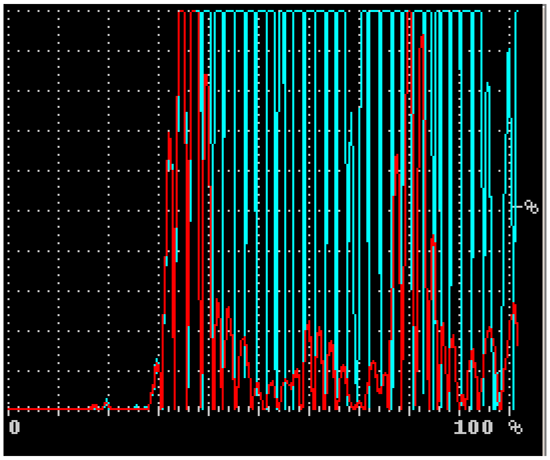
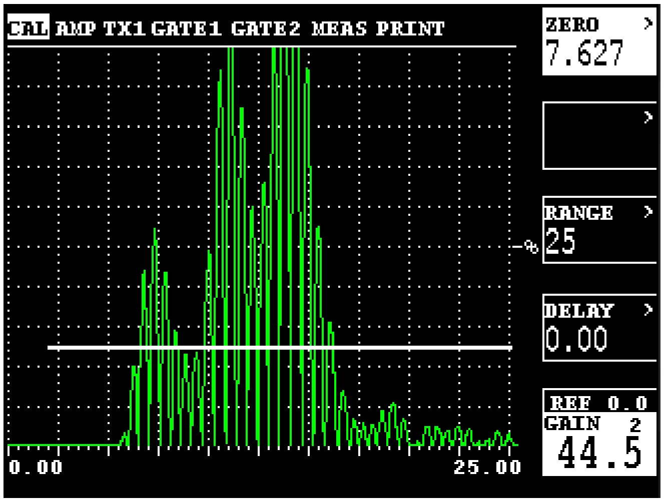


Fig 11

Fig.'s 12 through 14 help to further demonstrate the proper gain level. These are all velocity waveforms. For the velocity waveform, you need to balance the gain to get the greatest range while measuring the same lobe. The lobe of interest should be the first one that significantly rises above the baseline noise. It is usually best to have more room between the gate and the peak of the lobe than between the baseline noise and the gate. This is because it is more likely that the signal will loose amplitude while scanning over areas with surface build-up or reduction of couplant flow than the case of signal amplitude or baseline noise going up. This is dependent on the conditions and signal to noise ratio. In Fig. 12 the gain is too low, since the measurement is likely to change with a small amount of amplitude change by catching a different lobe. The slope of the signal edge is also less near the signal peaks. This should also be avoided on the thickness waveforms. Fig. 13 is a good gain level where the baseline noise can be seen at the bottom of the screen. In Fig. 14 the gain is too high and the baseline noise or a extraneous signal may trigger the gate measurement. Fig. 15 shows a thickness waveform with too low of a gain setting, where gain sensitivity will be a problem.



ZERO 7.627

RANGE 25

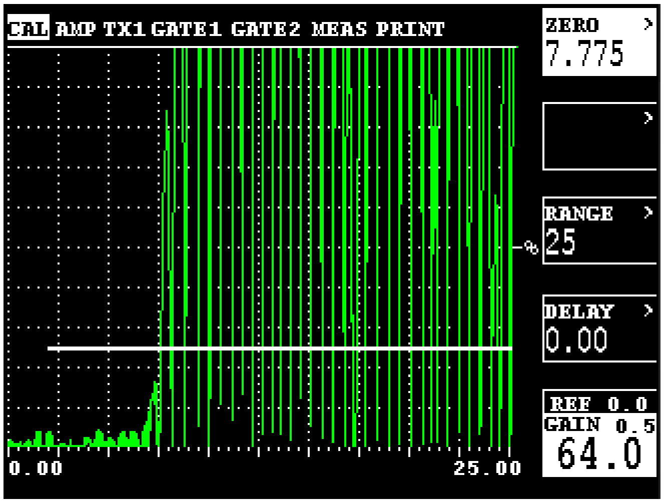
DELAY 0.00

REF 0.0

GAIN 2

44.5

Fig 12



ZERO 7.775

RANGE 25

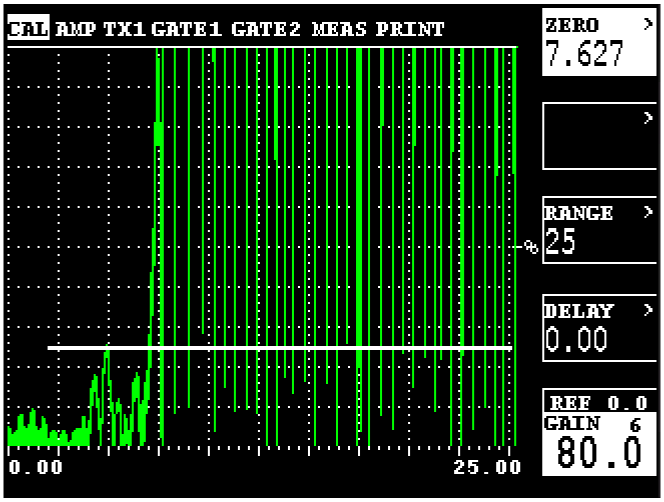
DELAY 0.00

REF 0.0

GAIN 0.5

64.0

Fig 13



ZERO 7.627

RANGE 25

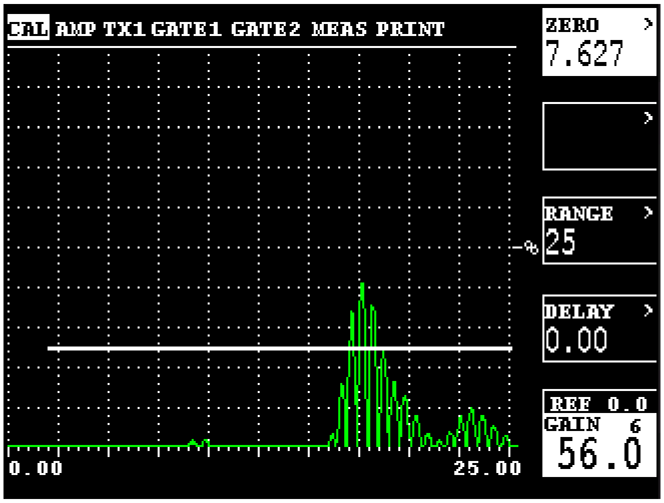
DELAY 0.00

REF 0.0

GAIN 6

80.0

Fig 14



ZERO 7.627

RANGE 25

DELAY 0.00

REF 0.0

GAIN 6 56.0

Fig 15

To sum up on gain, it is best to find a good level for the velocity signal and then insure that the thickness signals on both materials and steps are all above 90% screen height. The D2S system balances the gain between both waveforms for the best relative levels under varying conditions. Also, it is highly advisable to calibrate at a constant gain.

While scanning under actual field conditions, the signal amplitudes will not be as ideal as on the calibration blocks. The important thing to remember here is to try and maintain the first signal lobes at the same level as they were while calibrating for the most accurate readings. This means that you may have to vary the gain across the dryer roll scan. It is very important to monitor both the A-scan on the screen to check signal gate measurement and the b-scan on the computer screen. A main advantage with the D2S system is the ability to do both. If you suspect an area of bad measurements, simply have the crawler operator back up and drive over the area again, while you compensate the gain level.

Properly wetting the roll surface is very important for good results. Insure that the weep holes in the wedge are not clogged up from pulp or other particles. Travel at the fastest speed at which you can properly monitor the scan and maintain good coupling. <u>If you can OK it with mill personnel</u>, pre-wet the rolls with a water or fire hose before scanning for better and faster results.

SCAN QUALITY

The D2S system was designed to minimize operator problems and make the inspection as dependable as possible while maintaining feasibility. However, this still requires vigilance on the part of the operator and the operator is still responsible for delivering quality data to the customer. In real world conditions, you will have a certain amount of data loss with any automated acquisition NDT system. It is the responsibility of the technician to minimize this as much as possible. This will vary greatly with the environment, since you may complete some inspections with “perfect” scans. Some paper machines may have older, more ultrasonically difficult rolls and some will have more surface build-up. If you have scans with more than just a few extraneous data points, check the system and couplant flow. Be suspect of greatly varying velocity data or sudden "jumps" in the velocity scan, since these are not likely in reality. If you cannot acquire a good scan in a reasonable amount of time, consult the customer and discuss any extra steps that may have to be taken, such as cleaning the rolls in extreme cases.

It is also important to take data on a sufficiently small interval. An interval of 0.250 inches is a good number since this is slightly smaller than the size of the thickness transducer elements. Scan speed at this interval is generally about a couple of inches per second. The D2S system is several times faster than any other known dryer scanning system, so speed should not be a problem. Full speed of the C1 Spider scanner can be realized at 0.500 inches per second (for multiplexed scanning), but longer data intervals than this are not advisable for good inspections. Smaller increments make extraneous data less significant and the higher sampling rate better validates scan analysis operations such as data clipping, interpolation of the velocity data, and moving average analysis.

Scan analysis functions such as clipping and velocity interpolation are available in an effort to increase the quality of presented data, and usage should be minimized as much as possible. The smoothing function should only be used when the interval is small compared to the size of critical flaw areas, and the data should always be presented as having this operation performed. It is used to help visualize data trend across the roll for scans with a lot of small variance data noise, and produces more probable values for the HI-AVERAGE-LOW display function. The clipping function should be used on greatly outlying data that the operator has properly evaluated as being extraneous. Actual grooves should be apparent with a reasonably small interval (small compared to the length of interest), since they should be apparent on several data points with either a data loss or smooth transition on each end that would demonstrate a physically reasonable groove. Analysis and statistical functions should act as an aid, but data integrity is the responsibility of the operator.

On another very important note, the customer assumes that the inspector is properly evaluating the quality of data he is taking. Any apparent detrimental shell loss should be examined more closely with a minimum of backing over the area and evaluating the A-scan more closely. The customer should provide nominal shell thickness before the inspection, as well as the critical thickness (sometimes called T-min.). The T-min function will place a red line at this value which will outline below-minimum values in red. If critical data is found on a roll, the customer will want a more critical evaluation so it is better to do this while you are set up on the roll than after packing up to leave. Also be aware of reasonable velocity values. Cast iron dryer rolls will reasonably vary between the following values:

0.1700 to 0.2100 inches per second.

Although values outside this range are possible, they should be suspect. Lower values will be found on older rolls (ex. 1940), and higher values should be expected on newer rolls and machines.

Finally, a note on the moving average function. In some cases, the governing body and/or code will allow averaging of thickness data over a length determined by the diameter of the vessel, etc. This means that a small area below the minimum thickness may be acceptable if it averages with the area around it to remain above this minimum. The exact placement of the averaged length may affect whether it remains above or below the minimum. The moving average moves across the scan averaging the number of points that equal this length "L" and placing this average in that data placement. For areas less than L / 2 from the ends, points comprising length L from the end are used. For all points further than L / 2 form the ends, the each point is averaged with those L / 2 on either side of it. This means that every combination of averaged length L is displayed on one line. You can make the customer aware of this function, and present these on a separate report printout if they request them.