SIGNAL ANALYSIS FOR AUTOMATED "GO – NOGO" INSPECTION OF COMPLEX GEOMETRIES USING ULTRASONIC PHASED ARRAYS

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Abstract: Ultrasonic phased arrays use multiple elements and electronic time delays to create beams by constructive and destructive interference. The phased array beams can be steered, scanned and focused electronically. As such, phased arrays offer advantages for the inspection of complex geometries.

An additional advantage of phased arrays is the capability to create a complete image of the part to inspect from a single probe position and to conduct signal analysis for automating the inspection. Time of flight and amplitude data from all the inspected volume can be analysed, treated and compared with a reference data set for generating a GO - NOGO result.

The case of interest consists of inspecting internal threads on an aluminum part. Certain parts are mistakenly threaded twice with a random angle of error between the two threading operations. Beyond a certain angle, the threads are weak and the parts must be rejected. A phased-array instrument performs an *electronic* scan using a 64-element probe, 15-element apertures, and 100 focal laws distanced by 0.5mm. As the angle of error increases, the signal amplitude from the tip of threads diminishes while it increases from the thread bottom. On each side of the threads are distinct mechanical characteristics (reference points) that allow locating precisely the position of the threads, compensating for various unpredictable variables. Using those reference points, two windows are overlaid on the scan image, the thread tip window and the thread bottom window. The ratio of energy in the tip window over the bottom window provides an accurate measure that allows the inspection instrument to accept or reject the part without human interpretation.

Introduction: Ultrasonic phased array technology offers solutions to the limitations of conventional UT. These include fixed probe characteristics (angle, focal distance and focal point size) requiring multiple probes, wedges and lenses to address a single application. This implies the requirement for mechanical movement for surface scanning which makes UT systems expensive and often and complex to use.

Phased array ultrasonic testing is an electronic method of generating and receiving ultrasound, which permits beam steering, beam scanning and beam focusing. A phased-array transducer is composed of several piezoelectric elements. In a phased array, each element is individually wired to a pulser / multiplexer and time delay circuitry. A selected series of these elements is fired with pre-determined delays to build up multiple wavefronts in the material under investigation.

The wavefronts interact, generating zones of constructive and destructive interference that yield the desired beam angle and focal spot position. By adjusting which elements are active and the set of time delays, the beams can be electronically steered and scanned to give complex inspection patterns. Using an array, hundreds of different conventional probes with varying angles and focal lengths can be simulated. An example of an angle beam formed from a linear array is shown below in Figure 1.

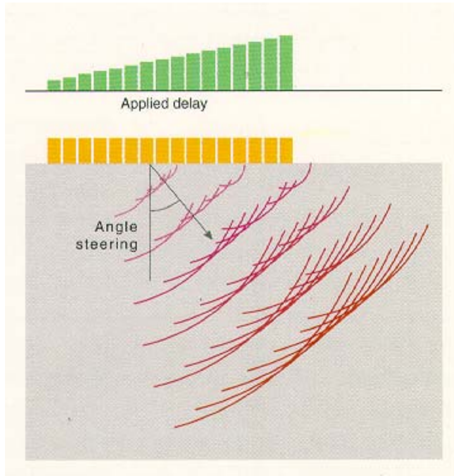

Figure 1: Forming an Angle with a Linear Phased-Array Transducer

The advantages of ultrasonic phased-array technology thus include a movement-free inspection via the electronic scanning capability which provides inspection speed, simplicity and reliability. Improved volume coverage is also obtained with PA thus enhanced detection performance. Finally, the available data imaging functions facilitates the data analysis and provide speedy error-free GO-NOGO sentencing capability.

Problem & Experimental Solution

This section describes how ultrasonic phased array technology is used to perform the inspection of parts that have internal threads on the last 50 mm (2 inches) of one extremity. The inspection is required due to an operator induced manufacturing defect that randomly causes certain parts to be double-threaded. Double threading in this case means that the part is inserted twice into the threading machine. Furthermore the position at which the threading starts, which is express in degrees from 0 to 360, is also random. A picture of the part complete with phased-array probe and wedge is shown in Figure 2.

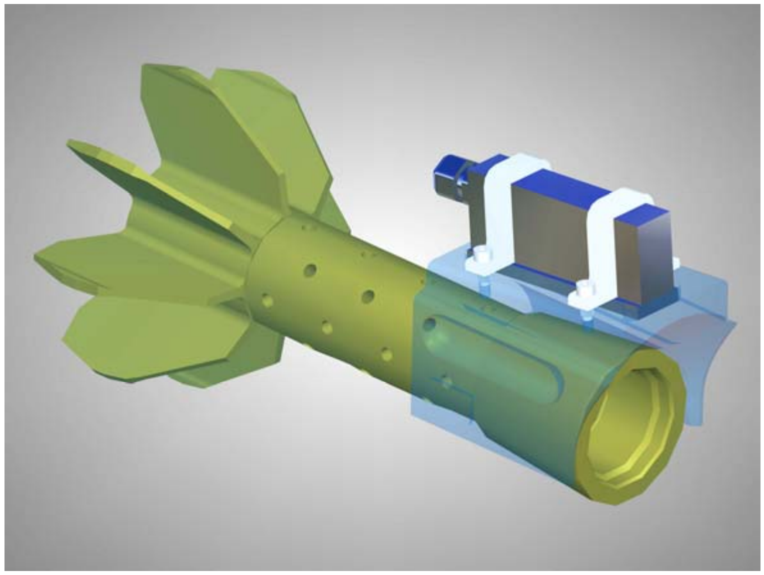

Figure 2: Part to Be Inspected Shown with Phased-Array Probe and Wedge

As the double threading offset, i.e. the difference in degrees from the first threading to the second progresses from 0 degrees towards 180 degrees, the bottom of the threads narrows, and the position of the bottom of the threads moves towards the mid-point between the tip and the bottom of the threads. At 0 degrees, most of the ultrasound reflections come from the bottom of the threads which presents a normal reflection surface. Little reflection comes from the sharp tips. At 180 degrees, this perpendicular surface disappears and reflection is diminished. Figures 3 illustrates how the threading offset affects the thread condition thus the reflective surface.

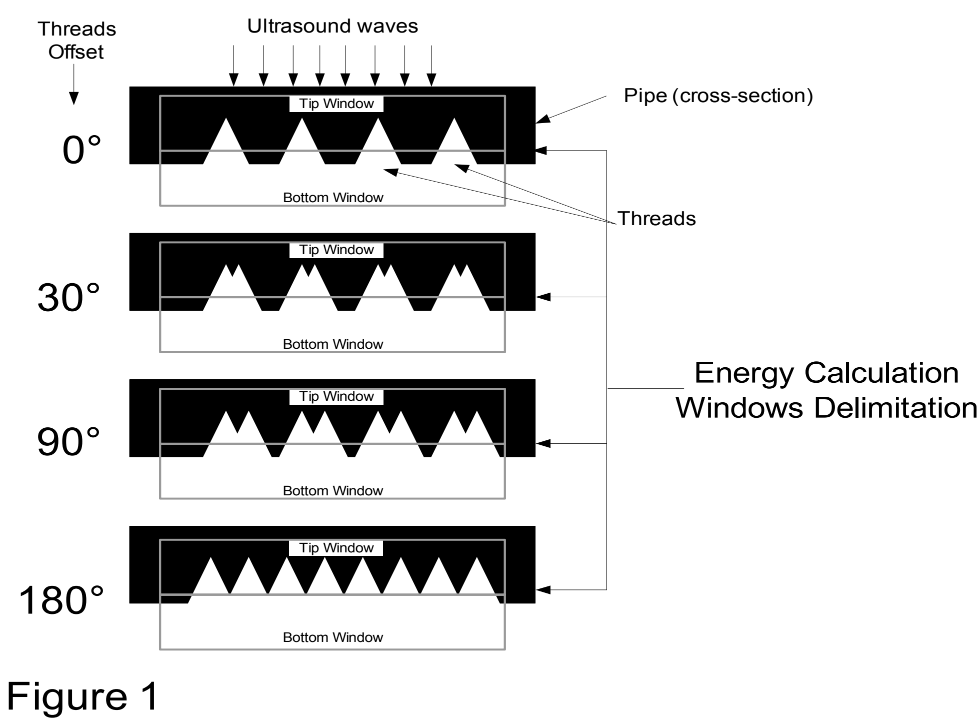

Figure 3: Effect of threading offset on thread reflective surface

Exploiting these observations, a method was conceived to compare the reflection energy from the thread tip area against the thread bottom area using a linear scan image, in which we define two windows delimiting the thread tip from the thread bottom areas. In each window, the average energy (the sum of all signal amplitudes divided by the number of samples) is first calculated. Subsequently, the ratio of energy between the two windows is computed and used as the criteria for acceptance or rejection of the parts.

Figure 4 shows a sectorial scan (S-Scan) of a good part, i.e. one that has not been double threaded. The right window containing the high amplitude dots corresponds to the thread bottom. The left window containing the low amplitude dots corresponds to the thread tip. The energy calculations are displayed on the top of the S-Scan. Similarly, Figure 5 shows a S-scan of a bad part with a thread offset of 90 degrees. Note how the thread tip and bottom signals have changed, and the energy ratio has increased.

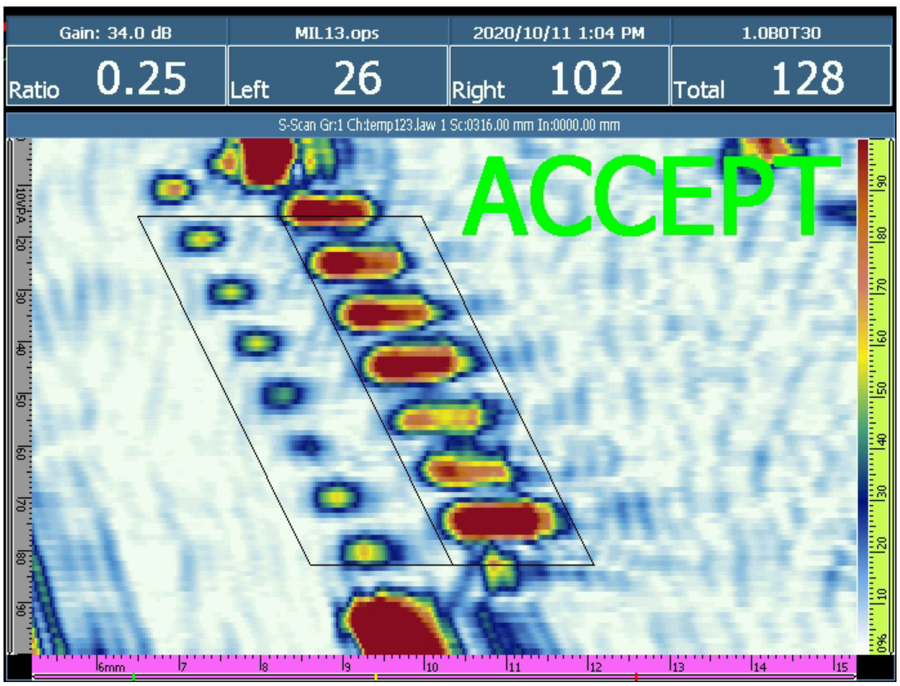

Figure 4: S Scan of a Good Part

The delimitation point between the two energy calculation windows is positioned such that the energy from the bottom of the threads appears in the bottom window at 0 degrees, or in the tip window at 180 degrees.

After having experimented with various window delimitation positions, it was found that the delimitation must be at the very edge of the signals from the bottom of the threads (at 0 degrees) in order to maintain the accuracy at low offsets. If the delimitation is too close to the bottom of the threads, accuracy is lower at low offsets but higher at high offsets. If the delimitation is too close to the tip of the threads, accuracy is lower at high offsets and the calculated ratio of a 180-degree part can be confused with a low offset angle part.

The position of the energy windows delimitation is thus critical. It was found that several variables may affect the results. These include variations of temperature and propagation delays as well as variations in coupling between the probe, wedge, and tail assembly introduced by the amount of coupling fluid used and the pressure applied by the operator. These factors may also change the angle at which the threads are scanned by the probe. An automated mechanism was therefore developed to perform the energy window positioning adjustment in real-time during the inspection.

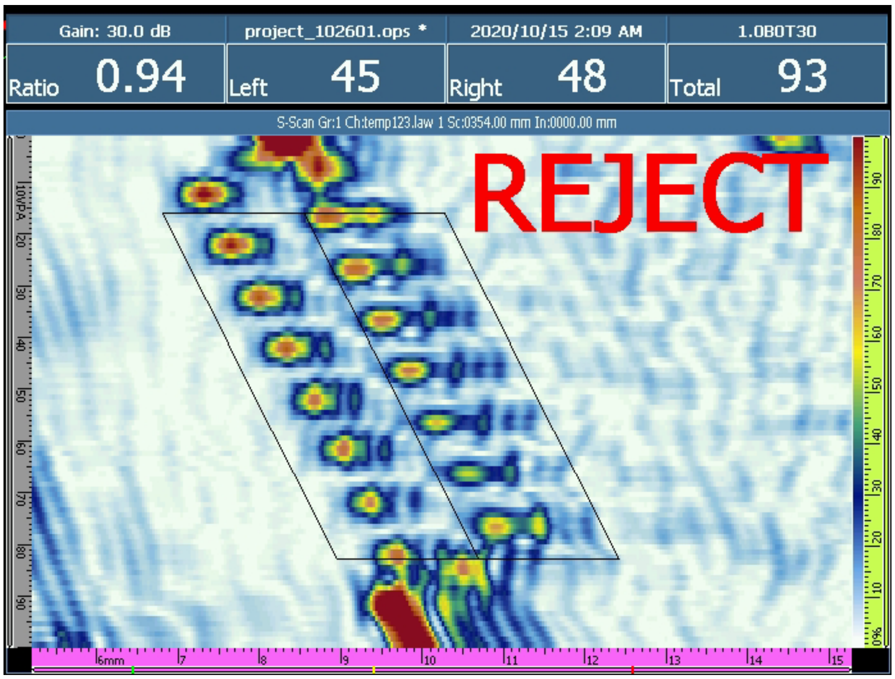

Figure 5: S Scan of a Bad Part with a 90-degree Threading Offset

Automatic Window Positioning Adjustment

As mentioned above, many variables can affect the energy calculations. Combined, all these factors make it quasi impossible to statically position the delimitation of the windows for energy calculation. Positioning must be dynamic and automated to facilitate the repetitive inspections.

The edges on each side of the threads are not affected by the double threading and are used as reference points to determine, in real-time, the position of the threads and the delimitation between the windows for energy calculation. This automated mechanism relies on the mechanical design tolerance of the tail assemblies. Two signal peak-detection gates are positioned where the edges are expected to be found, with a certain tolerance (position and width) for the aforementioned factors. Referring to Figure 6, the distance at which an edge signal is found is used to calculate the coordinates of the three window points close to that edge. The position of the edge signal in Gate A determines the coordinates A1, A2, and A3 of the windows. The position of the edge signal in Gate B determines the coordinates B1, B2, and B3 of the windows.

Coupling Detection

The system uses signals in gates A & B to determine if the probe has been coupled with the part. Once coupling is confirmed, the position of these signals must be stable for 2 seconds before the coupling check is confirmed and a result is produced.

Coupling Check

The system checks that the coupling is satisfactory by comparing the sum of energy in both windows against a range threshold. Insufficient or excessive energy results in an error warning and no result is produced. Insufficient energy can be caused by a lack of coupling gel or wrong positioning of the wedge on the part. Excess energy can be caused by an excessive gain applied to the signals, saturating the signals and corrupting the calculations. If the coupling check is successful, then the energies and ratio are calculated.

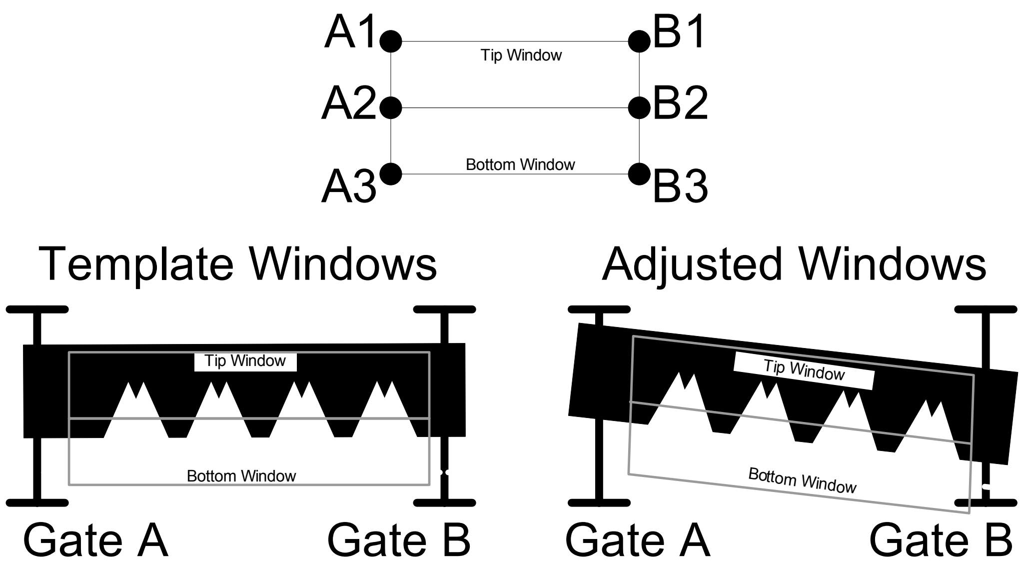

Figure 6: Energy Windows Positioning

Energies and Ratio calculation

Once the ratio is obtained, it is compared against a threshold. Fracture mechanic analysis dictated this threshold required to be set such that all parts that have been double threaded with an offset greater than 30 degrees are rejected. After performing experiments over hundreds of parts, and making a statistical analysis over the results, a threshold was set to ensure that 100% of the 30 degrees offset were rejected. This meant that occasionally, offsets of 20 degrees would be rejected; however the performance of the system was such that it would never reject offsets below 20 degrees.

Results: Table 1 below summarizes the results obtained from performing 30 tests on each of the 11 parts having a different threading angle offset. For each offset, the table shows the minimum ratio, maximum ratio, average ratio, and standard deviation.

Offset	**0**	**5**	**10**	**20**	**25**	**30**	**35**	**90**	**120**	**150**	**180**
MIN	0.25	0.33	0.43	0.57	0.61	0.66	0.71	0.86	1.10	0.93	1.19
AVG											

	0.28	0.36	0.47	0.64	0.69	0.75	0.78	1.00	1.25	1.09	1.48
MAX	0.30	0.39	0.50	0.70	0.74	0.82	0.85	1.12	1.37	1.31	1.91
STD	0.01	0.01	0.02	0.04	0.04	0.04	0.04	0.07	0.07	0.07	0.17

Table 1: Results Summary obtained from 30 Tests per Part

The accuracy of the inspection technique is well within the requirements that were originally set. In the 0 to 30-degree range, where the threshold for rejection was set, the measured ratio correlates to a specific offset plus or minus 5 degrees.

Over 2000 tests were performed and statistically analysed to validate the inspection approach prior to the actual inspection project. The results were found to be similar and consistent. In the manufacturing plant, over 20,000 parts were successfully inspected as shown in Figure 7. The reliability of the inspection system was again demonstrated by destructive testing of identified faulty parts.

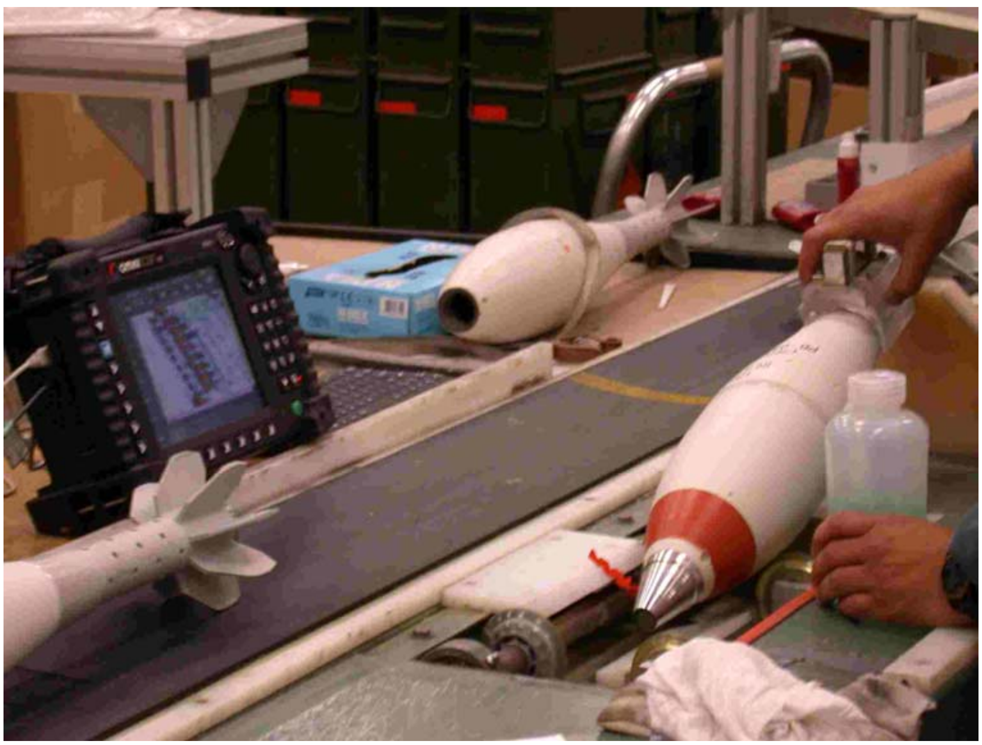

Figure 7: Automated Go-NoGo UT Phased-Array System in Plant Environment

Discussion: The automated GO-NOGO UT phased array inspection approach designed for the inspection of threaded parts was subjected to extensive testing and to a Failure Mode Analysis (FMA) in order to ensure its reliability. In addition to the variables described above, The FMA also addressed other factors such as wedge design which could lead to misalignment of the probe with the part. It led to a final U-shaped wedge design that completely surrounds the part and ensures proper alignment with the pipe. Furthermore, two additional signal gates were positioned ahead of the thread signals in case the wedge was not properly positioned and that the surface echo was mistakenly interpreted as reference points.

The spreading of coupling gel was also considered during the FMA. Excess of coupling gel creates a long period of instability while the operator applies the wedge against the part and for that reason a stability detection mechanism was implemented. It consists of a delay during which the signal amplitude must be constant for a result to be given. Lack of coupling gel tends to even the average energy in both energy windows*, and* thus may corrupt the results. To cope with this problem, a minimum energy threshold was implemented as a condition for producing a GO-NOGO result. Uneven spreading of gel was found not to be a problem provided that there is enough energy to satisfy the coupling criteria. Lack of gel affects the signal in both windows in a proportional manner.

The temperature was found to affect the propagation delays. Tests were performed between -20° C and +40° C. The variations were handled by the automatic windows delimitation positioning mechanism.

Conclusions: The capability of the UT phased-array technology to create a complete image of the part to inspect from a single probe position and to conduct signal analysis for automating the inspection was demonstrated. Time of flight and amplitude data from the inspected volume of the complex geometry part were analysed, treated and compared with a reference data set for generating a GO - NOGO result.

Moreover phased array technology allowed the implementation of an inspection technique that is mechanically easy to conduct, capable of being performed by a relatively unskilled operator, and less prone to error.

References:

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