Phased Array Ultrasonic Inspection of Structural Bolts Using Creo Bolt Scanner

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Abstract
Structural bolts are crucial in ensuring the safety and reliability of buildings, infrastructure, pipelines, and bridges. This paper comprehensively examines structural bolts using Phased Array Ultrasonic Testing (PAUT) and Total Focusing Method (TFM) with the Creo Bolt Scanners. The study aims to highlight the advantages and capabilities of this advanced inspection technique in both structural steel building and bridge applications. The inspection trial involved bolts with induced cracks and notches simulating defects. PAUT scans were performed in a circular pattern from both ends of the bolt, and TFM scans were employed to enhance flaw visibility in specific regions.

Keywords: Phased Array, TFM, 3D, Bolt Scanner, Render, Profile, Analysis.

1. Introduction

Structural bolts are critical components in construction and pipeline applications, providing essential connections and anchor points that ensure the immovability and safety of various assets. The integrity of these bolts is paramount to prevent potential failures and ensure the longevity of infrastructures such as oil and gas lines, wind towers, dams, riser pipelines, etc. Traditionally, bolt inspection methods have been time-consuming and expensive, often requiring bolts to be removed for visual examination or replaced after a set time period, regardless of their actual condition. No phased-array guidelines are described in international standards yet. Fortunately, it might appear soon as we see PA/TFM inspections being pushed forward. Right now, the few recommended practices are single beam inspections such as forged parts in ASME V Appendix IV, ASTM and ISO standards.

PAUT and TFM allow for the examination of bolts without disassembly, providing accurate and reliable inspection results in a fraction of the time required by traditional methods. In addition to the high-resolution ultrasound strategy, the integration of the bolt scanner further enhances the efficiency and effectiveness of PAUT inspections, enabling recorded, repeatable, and easily accessible data for future analyses.

1.1 Objectives of the Study

The primary objective of this research paper is to investigate the application of Phased Array Ultrasonic Testing with the Creo Bolt Scanner for the inspection of structural bolts in construction and bridge projects. The study aims to assess the capabilities and advantages of this advanced inspection technique compared to traditional bolt inspection methods, to evaluate...
the accuracy and reliability of the innovative approach and assess the potential benefits of using the Creo Bolt Scanner, such as enhanced data recording, setup efficiency, and inspection speed.

However, it is essential to note that this study does not cover the inspection of bolts in other specific applications, such as aerospace or marine environments. In addition, the research does not address other NDT methods, as the emphasis is placed on the evaluation of PAUT and TFM in the context of structural bolt inspection. By investigating these objectives within the defined scope, this research paper aims to contribute valuable insights into the effectiveness of PAUT with the Creo Bolt Scanner in ensuring the integrity and safety of structural bolts in the construction and infrastructure industry.

2. Methodology

2.1. UT Testing Background

Phased array brought tremendous new capabilities for NDT. The instrument and PA probe can steer and focus over a much larger region of interest (ROI) than single-element transducers. Applying the PA/TFM advantages to bolt inspection shows:

- Less scanning time because of its large ROI coverage.
- Full volumetric data when the acquisition is encoded.
- Increased accuracy and precision on detection, dimensions, defect profile and resolution.
- Advanced analysis software with imaging-based data allows an improved probability of detection and characterisation of defects for the technician; data can also be extracted in CSV formats for artificial intelligence (AI) algorithms.

Bolt inspection requires all the advantages of the phased array detailed above, so the NDT solution provides repeatable and traceable evaluation records. The effort of improving the bolt inspection would also require establishing the following key points:

- Scan plan optimisation, ensuring the probe position is set and the optimal angles and focusing planes are used for the bolt under examination.
- The encoding strategy ensuring the full circumference of the bolt is scanned.

2.2. Sample Selection and Preparation

Three bolts were carefully selected as specimens for this research. Each bolt was deliberately chosen to have known, surface-breaking flaws, mirroring the defects typically discovered through conventional inspections like conventional UT, visual examination, penetrant testing, or magnetic particle inspections.

The selection criteria ensured that the chosen bolts met the following key attributes:

**Known Flaws:** These bolts had intentionally introduced flaws, enabling controlled testing and precise evaluation of PAUT and TFM capabilities.

**Surface-Breaking Flaws:** The defects extended from the bolt surface into the material, replicating conditions detectable by traditional inspections.

**Realistic Locations and Orientations:** Flaws were placed where failures commonly occur in field bolts, ensuring the study's practical relevance.
2.3. The Experiment

This selection process creates a controlled testing environment that closely resembles real-world scenarios, allowing us to assess whether PAUT and TFM can match or surpass traditional methods in detecting surface defects in structural bolts. Through this evaluation, our research aims to advance the application of non-destructive testing techniques to ensure the safety and integrity of construction and bridge components.

The setup for ultrasonic testing in this research is straightforward and highly effective. It comprises three key components designed to ensure comprehensive defect detection in structural bolts:

**Sectorial Scan:** The angle sweep is crucial for uncovering flaws that may not align with the single crystal probe inspection's orientation, for example. The sectorial scan also guarantees that even if the probe is offset from the outside diameter of the bolt, the ultrasonic compression waves will still reach the desired surface with a sufficiently strong signal. On higher angles (70 and higher, and critically above 85 degrees), the energy and beam width will not be adequate for a successful inspection.

![Figure 1 Two S-scan quality maps showing the resolution at the focal plane (vertical dotted line): Vertical resolution on the left (white/blue is better, smaller focus response) and sensitivity map on the Right (red is better)](image)

The method of generating sound waves in the material differs for PA and TFM. PA generates a wave by pulsing a group of elements in sequence and using constructive interference to create a high-powered wavefront in the material. TFM pulses individual elements, with the resulting wave received on the remaining elements in the array, this is a comparatively low power wave. In this application, long bolts require higher transmitting power to penetrate the full length; PA generally has no issue with this. However, some instances may occur where this exceeds the limit of basic TFM. Plane Wave Imaging is a middle-ground solution to this issue, but this is not explored in this study.

**Total Focusing Method (TFM) Scan:** A TFM scan can be incorporated into the ultrasonic inspection process using the Veo3 equipment. The TFM Region of Interest (ROI) is set on the critical areas of a bolt, those most prone to cracking, e.g. contact points, groundwater level, etc. Due to the bolt's geometry, the LL (Longitudinal Longitudinal) propagation mode is optimal for the TFM scan. TFM offers exceptional sensitivity and resolution, optimizing the visual representation of defects in contrast with the threads. Importantly, TFM provides higher fidelity...
results in areas of a bolt where PA and Conventional UT encounter high amplitude internal reflections, such as the bottom of the bolt head, for example, the surface geometry created by a reduction in bolt diameter may be essential to detect so the inspection mentions if it is correctly evaluated.

A coloured map can be generated to show signal strength and resolution quality for a specific region (as seen in Figure 2). In the PA setup (see Figure 1), when observing at a depth of 6mm, the point located at the thread creates the smallest focusing size. The TFM setup (Figure 2) provides a uniform focus size response along the thread and across the bolt diameter. The focus profile is shown in figure 4.
2.3.1. Quality Map Simulation

A good PA and TFM scan plan is required to provide good vertical and horizontal resolution, as well as a good signal strength in the target area, to ensure our scan plan is acceptable, using the Beamtool\textsuperscript{1} beamset tools, we can generate the predicted sensitivity maps for beam strength, horizontal and vertical resolution, and focal areas. The coloured quality map is a visual prediction where the previously mentioned metrics will perform the best. There is also a relative quantification of those quality measurements; therefore, it is possible to compare our two PA and TFM quality map scan plans.

2.3.2. Bolt Imaging Quality

Bolt dimensions cover a wide range of lengths and diameters. The PA and TFM imaging quality can decrease in longer bolts, especially in detecting thread dimensions, as shown in the Figure 5 quality maps.

The S-scan resolution and sensitivity will be optimized on a very tiny line where the focusing points are. On the other hand, the TFM quality map should be more regular across the entire bolt ROI. TFM would not create a severe loss of focusing performance inside the same ROI.
The TFM imaging does not increase the near-field length, but in this case, the all-focused pixels solve the ideal focal spot for the receiving signals. Consequently, the thread (and identical defects) should also have a uniform size along the bolt height axis.

The amplitude response will considerably change. The deep ROI causes low amplitude thread echo, and indications might disappear by the attenuation effect and the decreasing focusing field effect. We thus recommend using a TCG calibration based on the same material and bolt length on both TFM and S-scan strategies.

3. Results
This section presents the outcomes of our structural bolt inspection data. Through Phased Array Ultrasonic Testing (PAUT) and Total Focusing Method (TFM) using the Creo Bolt Scanner, we reveal insights from a 0.5 mm (0.020”) precise EDM machined notches on an anchor bolt bar and another wide thread bolt sample. These findings, along with their analysis and comparisons with traditional methods, provide a compelling vision for the future of structural bolt assessment.

3.1. The S-Scan and TFM Views
The instant view of a sectorial scan combined with the 360-degree encoder acquisition; the dataset contains a full 3-dimensional bolt volume. Using extraction boxes, the encoded top view will provide the circumferential profile, hence the notch depth and length. The side view will provide the thread side view, as well as the notch length and height location. The sketch below displays the bolt and its view representations. It helps benefit this study, but also during the inspection, displaying the scrolling bolt data.

![Figure 6 Data Side and Top Views](image-url)

The side view unwraps the cylindrical thread into a cumulated B-scan flat view. The top view, though, shows the edge of the bolt surface. Reducing the box size can also make a slicer viewing feature if necessary. It then behaves like a zonal inspection tool against natural echo, for instance.
3.2. Notch Data

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Table 1 Machine Notch and Top View

3.3. Notch Length

Regarding the length evaluation, the shape significantly impacts the size. The beam width in the passive aperture axis was also larger than the indication size. Comparing the flaws to each other, the aggressive concave shape notch created an echo length twice as large even if the probe elevation is the same. A and C were 200% longer than B and D (indication letter reference the previous table). A and C are twice as big and twice as deep as the other indications, creating a larger beam response. The resolution quality is getting poorer the deeper it gets. The horizontal resolution indeed increases in size further away from the probe. This was predicted by the quality map tool in Figure 7. The amplitude echo is also higher at 6 inches down than 3 inches. A TCG calibration would then require a stronger amplification at the 3rd inch and less amplification at the 6th-inch reflector.

![Image](horizontal_resolution.png)

Figure 7 Horizontal resolution - Blue is better, yellow is the worst resolution region.

3.4. Notch Depth

The notch depth was, on the other hand, closer to the real flaw size because the active aperture improves the beam width (parallel to the active aperture). The effect of focal depth is also noticeable under the near-field range. A slight offset of the focal point and the thread will stretch the indication response.
The corner echo from the notch and thread junction creates a large reflection when the focal point is slightly away. For that reason, the error compared to the reference size was less significant using the TFM depth measurement. Oversizing is not a disadvantage this time, as detection is the main priority for bolt assessment. Small defects of 2 by 4 mm must be detected regardless of the bolt size.

3.5. The Importance of the Scanner and the Probe Position
To illustrate the impact of respecting the scan plan position, the following example brings an unfocused S-scan result with a TFM image, which is focused throughout the ROI. This scenario is similar to a probe placed incorrectly on the bolt head, forcing the focal plane to be incorrect. The threaded fastener section and the bottom are the most reflective insight that you get during an inspection. Although, the screw thread should not take a large place in the ROI because the geometry of the screw pitch and thread depth is rarely larger than 3 mm V-shape. In that case, the TFM will provide a cleaner thread image that is closer to its real dimensions, so any anomalies will appear in the threaded zone.

The uniform side view profile of the TFM data is also getting a more flattened back wall echo, allowing a better far surface resolution against the far threaded zone.
In the end, the geometric fidelity of the TFM recording provides a clearer view content the internal shape of the defect and the natural geometry echo from the bottom of the bolt (and other features like chamfer, natural corner traps region, etc.)

The probe is firmly sat on the bolt head, and the bolt scanner always applies a constant coupling pressure. In the ultrasound field, a reliable and controlled probe-to-piece interface delivers repeatable data and more accurate repeatable data. All the imaging information goes through that interface, and TFM acquisition needs a controlled coupling as well as any other UT techniques.

4. Conclusion
The combination of the latest imaging strategies, better scan plan preparation software and proper encoder scanning generates a lot of interesting key points. The probe remains stable and gets a constant offset, so the anticipated scan plan is respected and repeatable bolt after bolt. The combination of L-wave TFM and S-scan grants a full 3D volume of data. Extracting and slicing the side and top view from the recorded bolt elevates the post-analysis for a comprehensive interpretation of the bolt. The extracted TFM side view renders an insightful unwrapped threaded zone result, and it has the potential for computer and automated analysis intelligence. Adding side and top views aids in increasing the POD of defects that may be missed in a live scan of a bolt.

These recent ultrasound NDT strategies are vital for preserving critical and long-life assets like wind towers or flange bolts transporting hazardous and high-pressure content.

Reference for later


The reference point in the text should be formatted thus [1].