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OPTIMIZATION OF ULTRASONIC C-SCAN SYSTEMS FOR ACCURATE METROLOGICAL MEASUREMENTS AND INDUSTRIAL USE

Akash Koiri

Master's Student
Production Engineering
Sri Sai College of Engineering and Technology, Badhani Pathankot

Er. Saurabh Sharma
Assistant professor SSCET Badhani Pathankot

Abstract

Ultrasonic C-scan devices are central non-destructive testing (NDT) equipment that are commonly used in industrial, automotive and aerospace industries to identify internal flaws and carry out accurate dimensional analysis. This paper was set out to improve ultrasonic C-scan systems to achieve better metrological accuracy and reliability in the industrial case. Contact and immersion ultrasonics were performed comparatively on ASTM reference blocks through rigorous calibration against both IS 4904:2006 and ISO 2400:2012. A bespoke automated immersion C-scan was designed with servo controlled scanning capability, real-time echo acquisition and highly visualized data. The outcomes showed higher accuracy of the immersion technique, where the uncertainties were lower (thickness: 0.015 mm, attenuation: 0.38 dB/mm) than the contact method. The system managed to identify artificial flaws and demonstrate an overall uncertainty of 0.070mm, which confirms its industrial applicability. The present work develops the best ultrasonic C-scan techniques, which present useful instructions on high-precision non-destructive testing and quality assurance in sensitive engineering fields.

Keywords: *Ultrasonic C-scan, Non-Destructive Testing (NDT), Metrology, Immersion Testing, Thickness Measurement, Defect Detection, Industrial Inspection.*

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1. INTRODUCTION

Advanced non-destructive testing (NDT) techniques such as ultrasonic C-scan systems are used in industrial, automotive and aerospace industries to determine the structural integrity of materials. In this method of inspection, high-frequency sound waves are used to penetrate material. Internal flaws such as holes or cracks will reflect ultrasonic waves to generate echoes that are used to generate two-dimensional (C-scan) cross-section images. Internal structure is demonstrated on these scans, which allows precise evaluation of material conditions. The preference of the ultrasonic C-scan systems is based on the fact that they are non-destructive or minimally invasive, non-destructive, and capable of identifying even minor defects within a short period. The technologies are automatable to enhance repeatability and efficiency of inspection. This necessitates the use of ultrasonic C-scan systems in order to ascertain that structural components meet regulatory standards and maintain safety and performance in most cases.

The non-destructive testing also guarantees reliability and durability of materials and construction without damage. Ultrasonic C-scan is imperative in determining physical characteristics, locating defects, and obtaining the correct dimensions in regards to metrology. Such methods allow constant monitoring of the components in such industries as aerospace, automotive, and construction where safety and high standards are essential, thus preventing disastrous collapses and reducing maintenance expenses. Manufacturing and maintenance Ultrasonic C-scan systems are used to inspect large structures and complex geometries. They even ensure safety and weight reduction in the aerospace by checking wing structures and fuselage panels. They detect faults in the weld structures of automobiles so that they can be reliable. The energy industry employs ultrasonic C-scans to check on the pressure vessels and pipelines as a means of safety in their operations. The ultrasonic technology may be incorporated in automated inspection systems to enhance the accuracy and efficiency of industrial processes.

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1.1. Objectives of the Study

This study aims to:

- To identify and analyze the key factors that influence the performance of ultrasonic C-scan systems, including transducer selection, scanning techniques, and data processing algorithms.
- To develop optimized scanning protocols that improve measurement precision and reduce uncertainties associated with ultrasonic testing.
- To evaluate the impact of various environmental conditions on the performance of ultrasonic C-scan systems and establish guidelines for optimal operating conditions.
- To integrate advanced signal processing techniques that enhance image quality and accuracy in detecting defects and material properties.
- To assess the applicability of the optimized ultrasonic C-scan systems in real-world industrial scenarios, focusing on their effectiveness in non-destructive testing and quality control processes.
- To provide recommendations for industry practitioners on best practices for implementing ultrasonic C-scan technology in metrological measurements, thereby fostering greater adoption and standardization in various sectors.

2. LITERATURE REVIEW

Ma et al. (2024) applied signal correlation to detect delamination faults in two-dimensional carbon fiber reinforced plastics. This method enhanced ultrasonic testing by differentiating between normal and abnormal signals particularly with low amplitude and graphically showing severity of defects. At the same time, the echoes on both sides of the ultrasonic detector were combined to retrieve low fault signals in high-attenuation materials. The raw ultrasonic signals were first filtered using empirical mode decomposition and then the results of the two sides were combined with intelligent thresholding, and erroneous echoes were identified. Photographs of defects were

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created as well as size and depth computations. The method was able to identify artificial delamination's in carbon fiber laminates with an accuracy of less than 4 percent in depth and less than 0.5 mm in size.

Vo et al. (2023) praised scanning acoustic microscopy (SAM) based on its non-destructive internal material feature and fault detection. They discovered that the scanning time has a significant influence on the efficiency of industrial SAM product line inspection. Industrial sample evaluation required SAM systems that were too slow and costly using traditional linear motor-based systems. In this paper, a low-cost, high-speed scanning acoustic microscopy (FSAM) system capable of quickly capturing high-resolution images was introduced. The slider-crank mechanism cut down the FSAM inspection times of some components. The scan speed led to bubble cavitation, which decreased the quality of images. Theory of incompressible flow and pressure tests revealed that bubbles were created below vapor pressure. They used a transducer bubble reduction plate to fix bubbles and treated pressure data using OpenFOAM. Aluminium and coin samples were scanned, and the quality of the pictures and the correct information inside the FSAM system was proved.

Yadav et al. (2023) described the layered measurements, faults, cracks and welding material assessments of ultrasonic testing. Ultrasonic immersion scanning devices find a number of industrial and metrological applications. The immersion was done on a computer after data was collected with a simple data acquisition device (DAQ) which is fast. Signal triggering and detection of transducer signals was performed using a pulser receiver module and useful data was extracted out of raw data using computerized signal processing and filtering. Their investigation developed an ultrasonic immersion C-scan testing system that used a commercial ultrasonic flaw detector (UFD) in place of pulser receiver and DAQ. Servo motors controlled five axes and scanning was automated using Visual Basic.NET software using user-defined ultrasonic attenuation, echo spacing and echo amplitude. This system confirmed its operation by thickness variations and ultrasonic contraction testing with a detection capability of defects of +/- 0.01 mm.

Zhong et al. (2023) defined top-off friction mix spot welding (RFSSW) connections and compared ultrasonic element-based C-scan imaging techniques in locating and measuring the piece

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boundaries. They wanted to find a way of automatically analysing and classifying items. The study revealed that the piece boundaries were described better in frequency-domain C-scan imaging as compared to time-domain imaging. Also, base material zone (BMZ) echo signal element value technique was more successful than piece echo signal-based C-scan imaging. The readings of the piece, analyzed in terms of the -6-dB drop-off method, were frequently higher than metallographic ones. The authors suggested that the Hough circle transform would be used to automatically calculate the sizes of joints based on the C-scan images. This technique enhanced size analysis and characterization of piece by eliminating the main frequency amplitude values of the BMZ in pieces.

3. RESEARCH METHODOLOGY

The research was carried out in order to optimize ultrasonic C-scan systems to achieve reliable industrial applications and correct metrological measurements. The methodology was split into three major steps: comparison of ultrasonic measurement methods, calibration of reference standards and development of an automated ultrasonic immersion C-scan system.

3.1. Comparative Evaluation of Ultrasonic Measurement Techniques

In order to evaluate the precision of measurement, ASTM reference blocks were measured using two ultrasonic procedures:

- **Contact Method:** The non-focused wideband 5 MHz transducer was lubricating oil couplant and Olympus Epoch 1000 ultrasonic flaw detector (UFD). The velocity of ultrasonic was measured according to the national standards traceable to National Physical Laboratory (NPL), India. It was a time-of-flight (TOF) based system that measured data that passed through the UFD and was confirmed with a digital storage oscilloscope (DSO).

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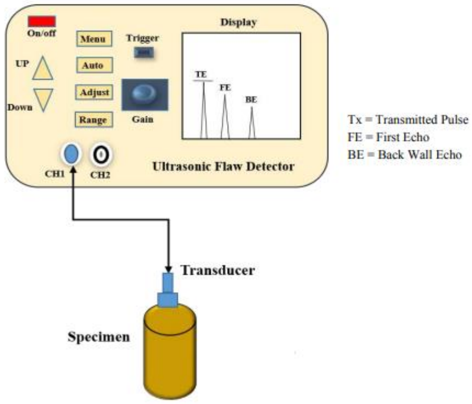

Figure 1: The ultrasonic contact method's experimental setup

In this case T is the thickness of the specimen (mm), v is the ultrasonic velocity in the material (m/s) and t is the transit time between the echoes (microseconds). The results of these measurements in the form of time-of-flight data were additionally verified with the help of a Lecroy Wave Surfer 42Xs-A digital storage oscilloscope (DSO) to make sure that the data is accurate.

- **Immersion Method:** The immersion system was a custom-made scanning tank of temperature 25 0.1 o C. The Marczak equation was dynamically modified to the recorded temperature to determine the velocity of sound in water:

$$v = 1.4023 \times 103 + 5.038813T - 5.799136 \times 10 - 2T2 + 3.287156 \times 10 - 4T3 - 1.39884 \times 10 - 6T4 \qquad (1)$$

where T is water temperature (°C).

Servo motors controlled the transducer along X, Y, Z, rotation (A) and tilt (B) axes in the scan of samples in water. Comparative findings assessed standard deviations and uncertainty contributions to suitable precision applications.

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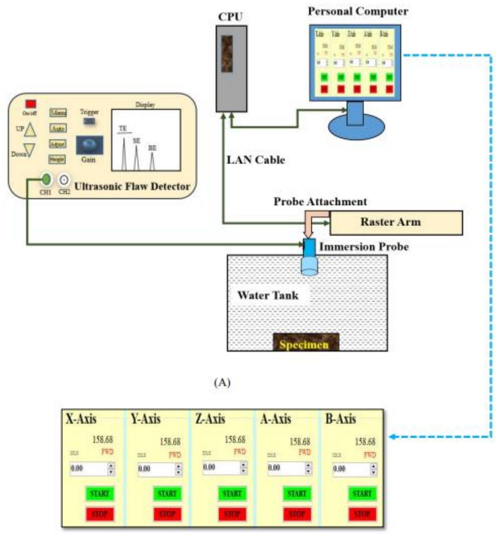

Figure 2: (A) The ultrasonic immersion method's experimental setup (B) An enlarged view of the motion control designed graphical user interface

Standard deviations, contributions of uncertainty, and applicability in high precision were considered by comparing both methods of thickness measurements.

3.2. Calibration of Reference Standard Blocks (RSB)

The traceability and adherence to the IS 4904:2006 and ISO 2400:2012 required calibration of IIW V1 reference standard blocks.

- **Thickness Measurement:** Digital height gauges, screw gauges and Vernier calipers were used, and each of them has several measurements to increase the statistical strength.
- **Ultrasonic Velocity:** Two methods were used:

1. **Using UFD Measurements:**

$$c_2 = c_1 \times \frac{d_2}{d_1} \qquad (2)$$

The actual velocity of ultrasound (c2) in the block was determined based on the estimated velocity input (c1) and the thickness reading of the ultrasonic flaw detector (d1) and the actual thickness as

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recorded (d2). The approach made sure that the parameters of velocity within the UFD reflected the material properties precisely.

2. **Using Direct Transit Time from DSO:**

$$c = \frac{2T}{t_d} \qquad (3)$$

Alternatively, velocity was calculated as a direct measure of the transit time (td) as measured by the digital storage oscilloscope (DSO). This offered a cross check of ultrasonic velocity, and increased the confidence in the measurement.

- **Attenuation Calibration:** In the case of attenuation, the coefficient was determined by the path length (d) between echo peaks and amplitude of successive echoes (H1 and H2). This allowed accurate measurement of the ability of the material to absorb and scatter ultrasonic waves.

$$\alpha = \frac{20}{d} log_{10}(\frac{H_1}{H_2}) \qquad (4)$$

3.3. Development of Automated Ultrasonic Immersion C-Scan System

A native ultrasonic immersion C-scan was developed with combined defect and metrological examination:

- **Hardware:** The system had a scanning tank that used a servo motor (X: 809mm, Y: 405mm, Z: 289mm, rotation, -1790, tilt -340) and an Olympus Epoch 1000 UFD that was interfaced via RS-232. Water was monitored by a temperature sensor to dynamically correct the velocity changes.
- **Software:** Tailor made software written in Visual Studio (.NET framework) allowed to control scanning parameters, movement of axes, UFD settings, and real-time data capture with precision. It facilitated automatic stepwise scanning, choice of pulsar and receiver settings and direct production of C-scan plots.

- **Testing:** The system was calibrated by scanning aluminum blocks with embedded twelve artificial defects (flat-bottom holes of different depths and diameters) and by mapping variations in thickness and attenuation in known samples.

This was a rigorous approach that encompassed comparative experimenting, stringent calibration and system development to result in an optimized ultrasonic C-scan system both in terms of defect detection and high accuracy dimensional metrology.

4. RESULTS AND DISCUSSION

This section provides an overview of the significant results of the comparative tests, calibration, and system validation, including better measurement accuracy, less set of uncertainties, and the success of the final ultrasonic C-scan system that can be used in industry.

4.1. Comparative Thickness Measurements

The measurement data for ASTM Reference Blocks 1 and 2 acquired using both touch and immersion techniques are shown in Table 1.

Table 1: Comparison of Contact and Immersion Methods for ASTM Reference Blocks

By Contact Method		By Immersion Method	
ASTM Reference Block 1 Thickness (in mm)	**ASTM Reference Block 2 Thickness (in mm)**	**ASTM Reference Block 1 Thickness (in mm)**	**ASTM Reference Block 2 Thickness (in mm)**
74.00	101.52	75.14	98.25
75.41	99.21	75.14	95.68
74.12	99.12	74.58	94.62
75.12	101.36	75.12	95.69
75.14	95.64	74.96	94.300
73.69	103.25	76.86	98.12
75.00	95.68	74.00	99.30

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74.16	99.99	75.14	99.00
Average = 74.58	**Average = 99.47**	**Average = 85.76**	**Average = 96.87**

The soaking approach produced a standard deviation of ±0.015 mm for block 1 thickness measurements, whereas the ultrasonic contact technique produced a standard variation of ±0.023 mm. The standard deviations for reference block 2 were found to be ±0.11 mm for the ultrasonic contact technique and ±0.02 mm for the soaking approach. We find that the coupling's instability causes higher deviations when the example aspects are physically scanned utilizing the touch approach. The identical measuring conditions were used in the two instances. The thickness data clearly show that there was undeniably less scattering during the inundation tests. providing couplant similarly between the test and the test object and providing no or very little strain to the test might have created the superior measurement uncertainty. It is dependably workable for a human to be involved with the test while employing the ultrasonic contact approach. The outcomes might become significantly more erratic subsequently. Besides, administrators utilize varying levels of tension on the test, or all the more precisely, varying levels of human intervention. The aftereffects of the submersion technique for thickness measurement are clearly below normal, as displayed in Table 1. This is fundamentally because of the layer of coupling material that is in close nearness and produces somewhat more worth. Likewise, the ultrasonic incident pillar may be somewhat slanted because of a non-uniform couplant thickness; this, in turn, could twist the ultrasonic bar and lead to sufficiency fluctuations in the received echo. We have attempted to apply the constant thickness of the couplant material. By and by, each precaution and wellbeing measure was taken during the current investigation to reduce the probability of such effects. The kind of measurement is displayed in Table 2.

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Table 2: Comparison of ASTM reference block type an uncertainty

Test Specimen	**Type A University**	
	By Contact Method	**By Immersion Method**
ASTM reference block 1	±0.015mm	±0.012mm
ASTM reference block 2	±0.075mm	±0.015mm

Table 3 provides a comprehensive uncertainty budget that considers all of the uncertainty input for the thickness measurement at the coverage factor (k=2).

Table 3: Uncertainty Budget: Immersion vs. Contact Methods

S No.	**Source of uncertainty**	**Probability Description Factor Division**	**Measured Value**	**Type of Uncertainty**	**Uncertainty Contribution in Contact method [33-35] (in mm)**	**Uncertainty Contribution in Contact method (in mm)**
1	Ambient Temperature ±2^{0}C	Normal √4	-	A	±0.075	±0.015
2	Height Guage	Rectangular √3	25.00 ^{0}C	B	±0.036	-
3	UFD (Thickness)	Normal √4	100mm	B	±0.04	±0.04
4	Water Temperature ±0.1^{0}C	Rectangular √3	-	B	±0.001	±0.01
5		Rectangular √3	25.00 ^{0}C	B	-	±0.002
6	Combines Standard Uncertainty (u, (t))				±0.099	±0.036
7	Expanded uncertainty at (k=2)				±0.180	±0.008

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The immersion approach is clearly better suited for applications requiring higher accuracy. The immersion strategy, however, calls for more advanced infrastructure, like a scanning tank. In certain situations, coarser accuracy applications may also call for the usage of the contact approach.

To assess the efficacy of the precise thickness measurements utilizing ultrasonic contact and submersion techniques on identical test objects, a comparative trial investigation was carried out. With the drenching technique, the specimen's thickness was all the more precisely and accurately estimated. Furthermore, the submersion case has a higher scanning accuracy. The study concluded that, depending on the application, the ultrasonic submersion method might offer a more precise choice for determining material thickness because it generated lower standard deviations in thickness measurements than the touch method. The touch approach produced standard deviations of ±0.014 mm and ±0.074 mm for reference blocks 1 and 2, respectively, but the submersion method produced tighter measurements of ±0.010 mm and ±0.014 mm

4.2. Calibration and System Validation

Thickness measurements of the Reference Standard Block (RSB) using Vernier calipers and screw gauges showed higher variability due to operator skill and parallax errors, while height gauges provided the lowest deviation and better traceability. To minimize bending effects, height gauge readings were taken on both sides. The contact (touch) method showed a standard deviation of ±0.04 mm, compared to ±0.014 mm with immersion. Using these thicknesses, ultrasonic longitudinal wave velocities were measured with a UFD at 4 MHz, yielding 5900 m/s by contact and 5901 m/s by immersion. The slightly higher velocity in immersion was due to eliminating coupling delays. Direct oscilloscope readings gave a transit time of 4.234 (±0.002) µs and velocity of 5902 (±3) m/s, though with higher variability due to RF echo thresholding challenges.

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Table 4: Budget uncertainty and its underlying factors

Parameter type	RSB Thickness (Ultrasonic Method)	Ultrasonic Velocity (Approach 3.2.1)	Variation Ultrasonic Alteration	Parallelism/ Perpendicularity
Type A	±0.003 mm	± 0.02 m\s	± 0.04 dB	± 0.02 dB
Type A	± 0.02 mm (height Guage)	±2.35 m/s (height Guage traceability)	-	-
Type B	± 0.02 mm (UFD thickness accuracy	± 2.35 mm/s (UFD thickness accuracy)	± 0.2 dB	± 0.02 mm (UFD Thickness accuracy)
Type B	± 0.04 mm (Temperature	± 0.16 m/s	Ignored as only change in dB measured	± 0.04 mm (Temperature effect ± 2 ^{0}C)
Combined Uncertainty	±0.35 mm	± 3.36 m/s	± 0.12 dB	± 0.030 mm
Expanded Uncertainty	±0.075	±6.85 m/s	± 0.21 dB	0.070 mm

Ultrasonic attenuation at 4 MHz measured by immersion was 29.87 dB, confirming material homogeneity within standard limits. RSB face parallelism and perpendicularity also met the ±0.1 mm tolerance. Table 4 summarizes combined and expanded uncertainties, all within IS 4904:2006 and ISO 2400:2012 requirements. This validated the RSB's suitability for high-precision ultrasonic calibration and highlighted immersion as the most reliable method for assessing attenuation and material uniformity.

4.3. Analysis of Ultrasonic Immersion C-Scan System Development

The ultrasonic C-scan system developed was tested on blocks to detect internal defects, variations in thickness of the blocks and variations in attenuation.

- **Defect Detection:** The system was able to detect defects using FBH blocks and 2.25MHz transducer and it identified the defect with the actual diameter of 6.0+/-0.5mm. The c-scan images clearly showed all the twelve artificial flaws present in the aluminum samples.
- **Thickness & Attenuation:** Variation in thickness was measured when scanning aluminum blocks and the variation was low with standard deviation of 0.015 mm and attenuation variation was between 0.38 dB/mm which confirms high precision of measurement.

The total uncertainty was measured as 0.070mm in thickness and 0.3dB/mm in attenuation, confirming that the system is reliable to use in the industry. The automated procedure led to high-resolution scans (down to 0.01 mm), minimized manual labor, and time, and reduced data volume, which makes it useful both in defect detection and metrological measurements.

Table 5: The system's combined uncertainty budget has been developed

S No.	Sources of Uncertainty	Probability Distribution Factor/ Divisor	Measured value Quantity	Sensitivity Coefficient	Type of Uncertainty	Uncertainty Contribution Thickness Measurement (mm)	Uncertainty Contribution Alteration Measurement (dB/mm)
1	Repeatability	Normal √4	-	1	A	±0.002	±0.20
2	Ambient Tank ±2 ^{0}C	Rectangular √3	25 ^{0}C	1	B	±0.004	Ignored the change in dB Measured
3	Immersion Tank (X - axis)	Normal √4	1mm	1	B	±0.005	-
4	Immersion Tank (in Y-Axis)	Normal √4	1 mm	1	B	±0.02	-0.2

5	UFD (Thickness)	Rectangular √3	-	1	B	±0.02	±0.3
6	Combined Standard uncertainty (u_c)					±0.070	±0.3
7	Expanded uncertainty at (k =2)						

Table 5 outlines the combined uncertainty contributions from repeatability, ambient conditions, immersion tank movement, and UFD measurements. The combined standard uncertainty was determined to be ±0.070 mm for thickness and ±0.30 dB/mm for attenuation, well within acceptable industrial limits. These values affirm the robustness of the developed system for precise defect characterization and metrological assessments in demanding industrial environments.

5. CONCLUSION

This research has been able to optimize the ultrasonic C-scan systems to attain high precision metrological measurements and accurate defect detection in industrial purposes. The research showed that, through systematic comparison of contact and immersion ultrasonic methods, calibration of reference standards according to IS 4904:2006 and ISO 2400:2012, and the creation of a custom automated immersion C-scan system, there was a considerable increase in the accuracy of measurements and the reduction of measurement uncertainty. The immersion technique performed better with smaller standard deviation and a total uncertainty of only 0.070mm of thickness and 0.3 dB/mm of attenuation. The system successfully detected artificial defects to within 0.5mm, created scans with a resolution of 0.01mm and reduced the need of human interaction, time and data volume. These results confirm the strength of the system and its viability in the industrial non-destructive testing and quality control, which offer useful methodologies and practical guidelines on how to improve safety, reliability, and standardization in the aerospace, automotive and manufacturing industries.

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