Rail flaw 3D imaging by enhanced ultrasonic synthetic aperture focus technique

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IHHA 2025
13TH INTERNATIONAL HEAVY HAUL ASSOCIATION CONFERENCE 2025

November 17-21, 2025 | The Broadmoor, Colorado Springs, CO, USA

Introduction

Internal rail flaws pose serious threats to railway safety, as undetected anomalies can lead to catastrophic rail breaks and failures. In North America, internal defects are one of the leading causes of track-related accidents, underscoring the critical need for reliable and accurate flaw detection techniques. Current rail inspections rely heavily on manual ultrasonic verification using the 6 dB drop method, a technique that is both subjective and prone to inconsistency in flaw sizing and characterization. The objective of this research is to demonstrate the feasibility and benefits of applying the Ultrasonic Synthetic Aperture Focusing Technique (SAFT) imaging methods in a roller search unit (RSU) to improve the accuracy, reliability, and speed of internal flaw detection and sizing in rail infrastructure.

Methods

This project uses the enhanced SAFT scheme to generate high-contrast and high-resolution 2D and 3D images by beamforming ultrasonic signals from matrix transducer arrays. SAFT enhances spatial resolution by synthetically expanding the aperture through coherent signal combination. Despite all the benefits by SAFT, raw ultrasonic video still suffers from low signal-to-noise ratio (SNR) due to limited array size, surface roughness, and material scattering. These issues introduce artifacts that obscure flaw signals and hinder accurate sizing. To mitigate these image artifacts, an unsupervised learning technique via recursive singular value decomposition (SVD) filtering is applied. By iteratively removing dominant signal components extracted by SVD, the filter suppresses background noise and highlights reflections from rail flaws. Finally, special post-processing algorithms are utilized to compile 2D images to a 3D volume and reduce the 3D point cloud into a result that can lead to the final size and shape of one (or multiple) flaws present in the scanned region.

Results

The rail flaw imaging RSU system based on enhanced SAFT methods was validated using test sections from the Federal Railroad Administration (FRA) defect library, maintained by MxV Rail. These rail segments included both natural and artificial defects. After ultrasonic scanning, test sections containing natural flaws were fractured to visually confirm flaw characteristics and establish ground truth. The imaging results showed strong agreement with the validated flaw geometry, particularly for natural transverse defects (TDs). Accurate reconstruction of flaw size and shape was achieved. These findings demonstrate that the RSU imaging system is capable of reliably detecting and characterizing internal rail flaws under realistic conditions, supporting the feasibility of 3D ultrasonic SAFT imaging in low-cost wheel-based scanning systems for improved rail safety inspection.

References

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Acknowledgments

This research was funded by MxV Rail under the “AAR University Programs – Grand Challenges in Railroad Technology,” contract No. 24-0312-008622. The authors acknowledge the technical support provided by Anish Poudel and Brian Lindeman of MxV Rail and Gavin Dao of Advanced OEM Solutions (West Chester, OH). The prior support of the US Federal Railroad Administration Office of Research, Development, and Technology under contract No. 693JJ619C000008 (Robert Wilson, Program Manager) was also invaluable for the earlier stage of the rail flaw imaging research.

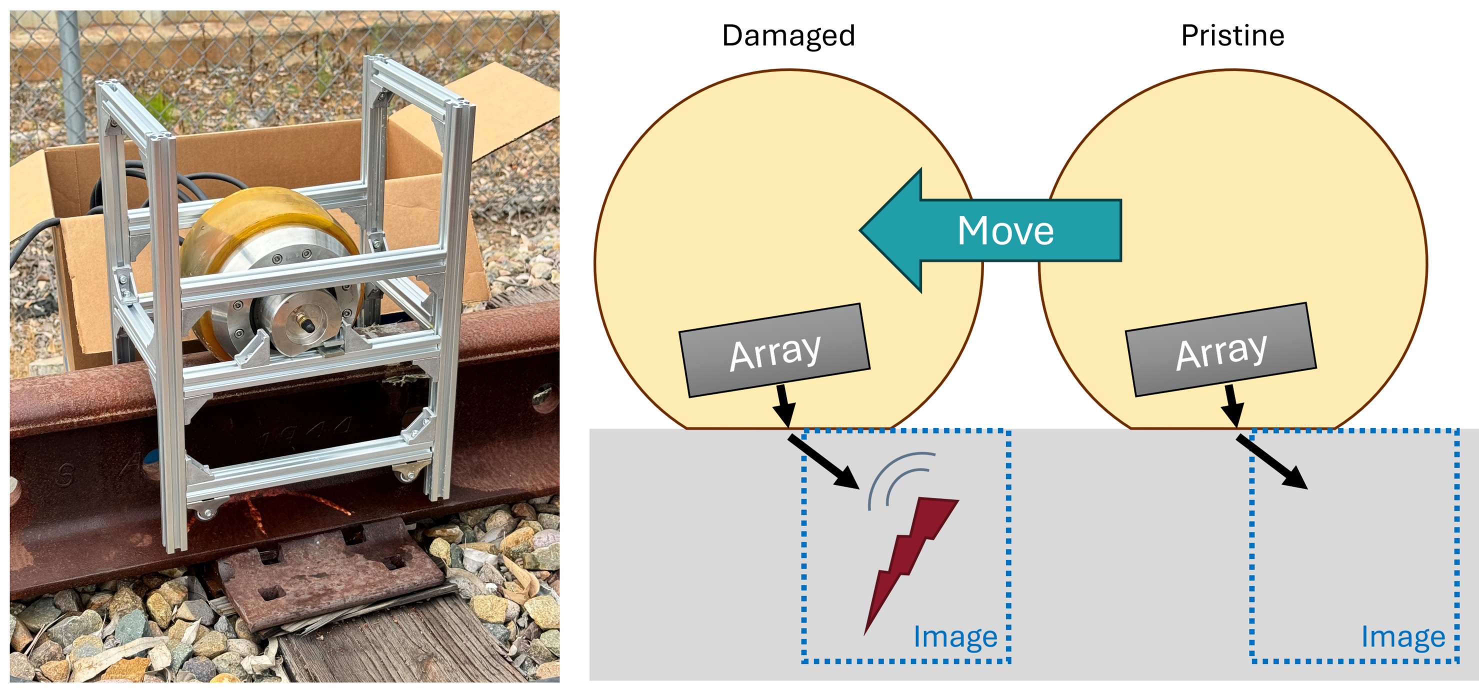

Figure 1. SAFT image generation from a roller search unit (RSU)

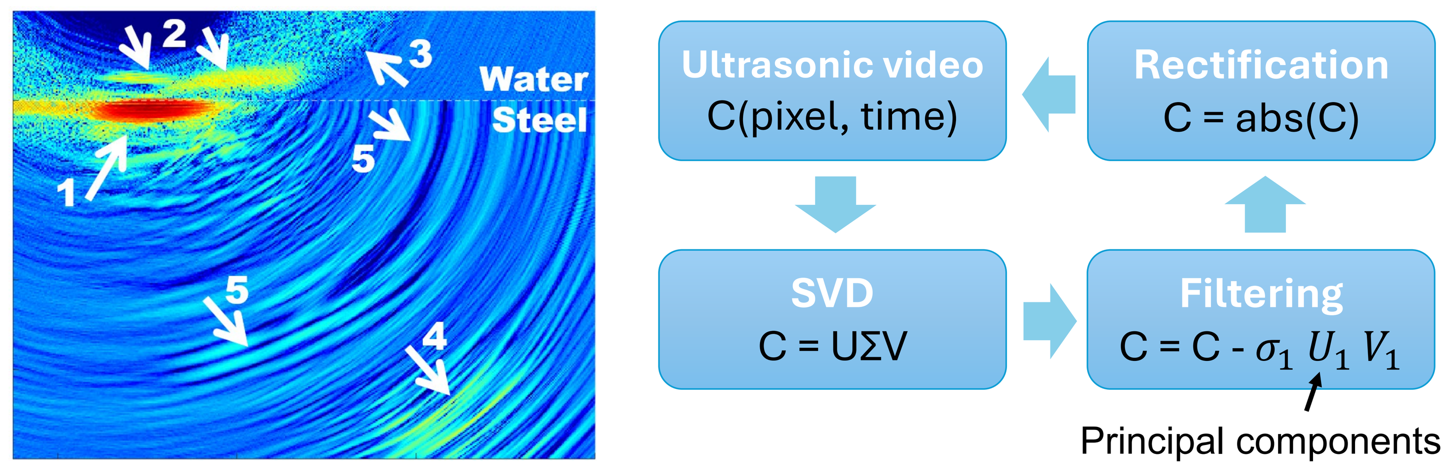

Figure 2. Unsupervised noise suppression by recursive SVD filtering

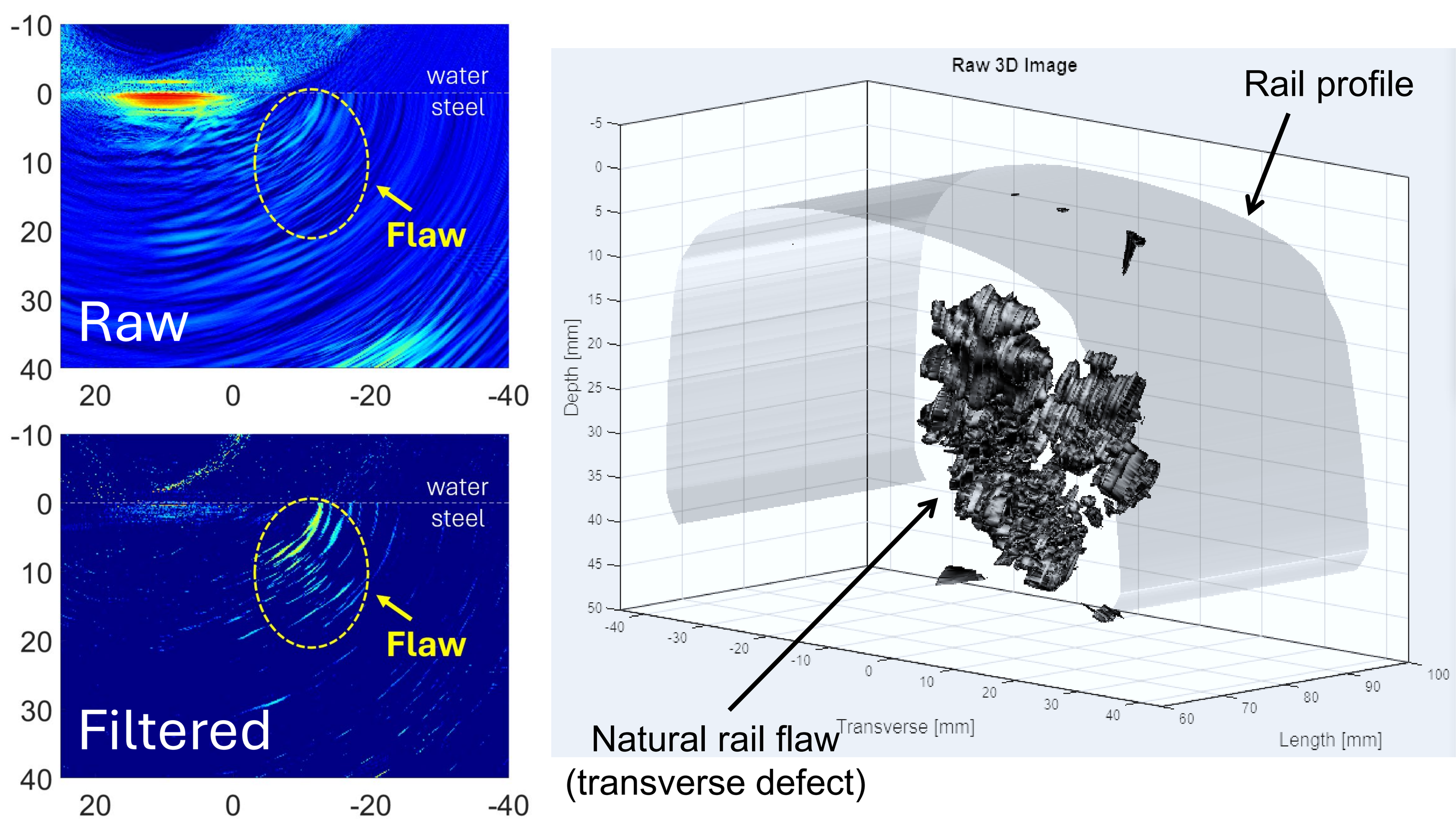

Figure 3: SVD filtering results and 3D rail flaw reconstruction

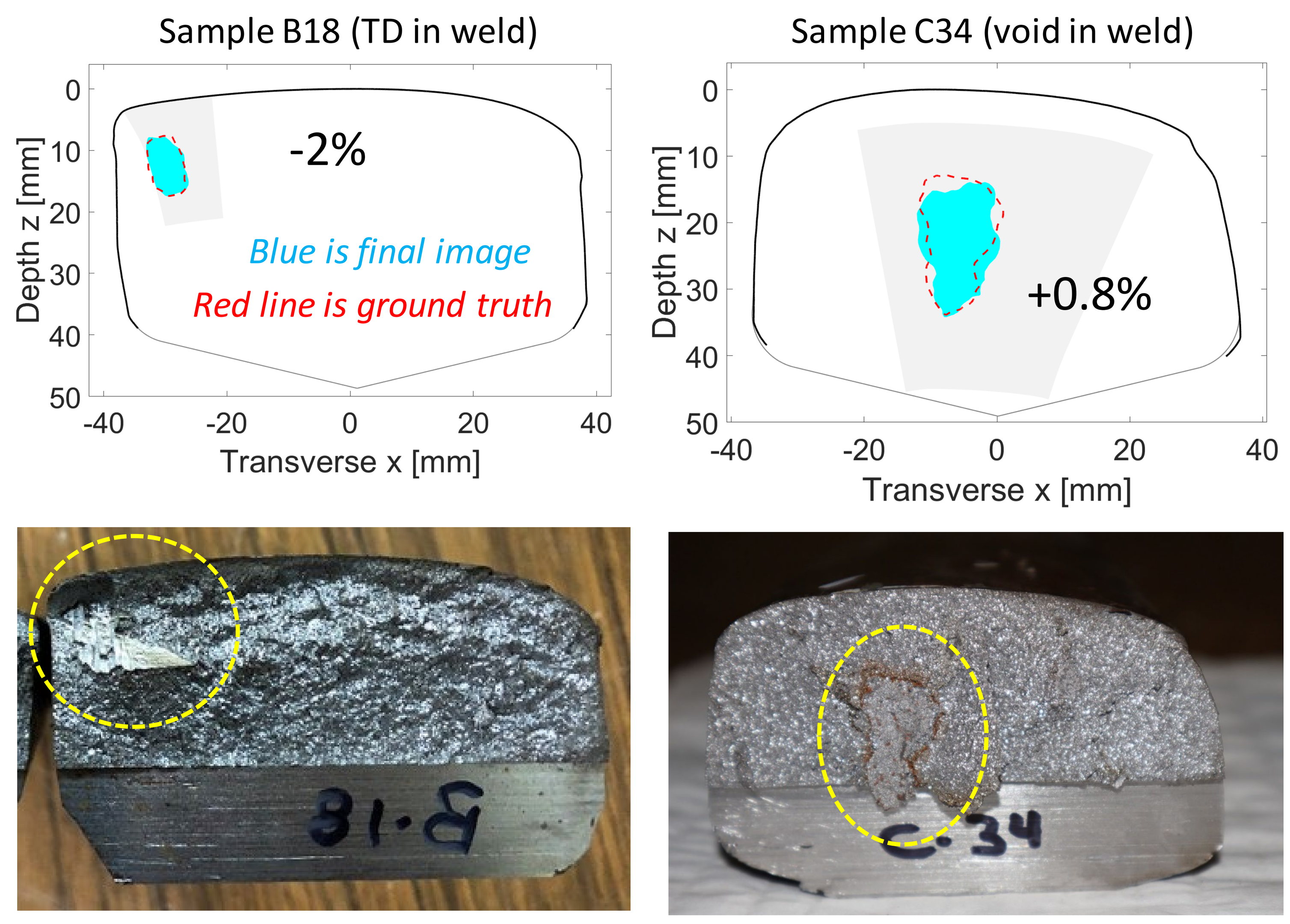

Figure 4. Validation tests on sections from FRA defect library

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