OFFICE OF RESEARCH & DEVELOPMENT

2012 R&D REVIEW

Ultrasonic Tomography for 3-D Imaging of Internal Rail Flaws

U.S. Department of Transportation
Federal Railroad Administration

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Program Area & Risk Matrix

Ultrasonic Tomography for 3-D Imaging of Internal Rail Flaws

Program Areas / Risk Factors	Trespass	Grade Crossing	Derailment	Train Collision	All Other Safety Hazards
Railroad Systems Issues					
Human Factors					
Track & Structures			X		
Track & Train Interaction					
Facilities & Equipment					
Rolling Stock & Components					
Hazardous Materials					
Train Occupant Protection					
Train Control & Communications					
Grade Crossings & Trespass					

Acknowledgements & Stakeholders

Acknowledgements

- High-Speed BAA 2010-1 contract DTFR53-11-C-00010 to Avanti Tech, LLC

Stakeholders & Project Partners

- Avanti Tech (grantee)
- Consultants from University of California, San Diego (UCSD), University of Pittsburgh, Drexel University and SUNY Buffalo
- BNSF Railway (data sharing on worn rail profiles)

Research Objectives of Project

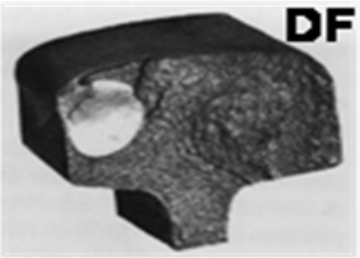
Develop the technique of Ultrasonic Tomography for 3-D imaging of internal rail flaws.

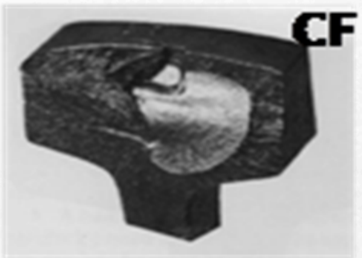
- **Phase I:** demonstrate Ultrasonic Tomography by Finite Element Analysis simulations

- **Phases II/III**: design and develop a Tomographic prototype and transition to railroads

Motivation for project

- Current rail flaw detection systems provide qualitative indication of flaws, <u>not quantitative information on flaw size.</u>
- Stop-and-confirm ultrasonic hand verifications result in highly subjective flaw sizing.
- High-speed rail requires accurate flaw sizing for well-targeted actions with short maintenance windows.
- "*Systems to perform 3-D imaging of internal rail flaws*" specifically listed as a topic under Track and Structures in High-Speed BAA-2010-1.



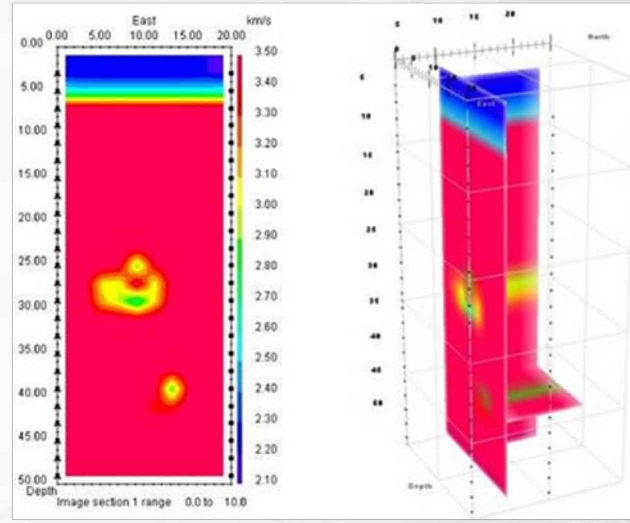


Examples of internal rail flaws

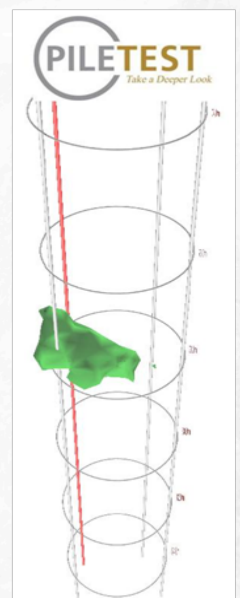
Technology Evolution

Ultrasonic Tomography already successfully used for 3-D imaging in other fields:

- Medical imaging (ultrasonic waves, electromagnetic RF waves, etc..)
- Sonar imaging (acoustic waves)
- Radar imaging (electromagnetic RF waves)
- Civil structures (ultrasonic waves)



Defect imaging in concrete walls



Defect imaging in foundation piles

Approach

Four key steps developed in this project for successful implementation of Ultrasonic Tomography for 3-D rail flaw imaging:

1. **Synthetic Aperture Focusing** (from Medical, Sonar and Radar Imaging)
2. **Matched Filtering** (from Radar imaging)
3. **Baseline Subtraction** (from Ultrasonic Testing)
4. **Multi-mode Detection** (from Ultrasonic Testing)

Tomography with Synthetic Aperture Focusing

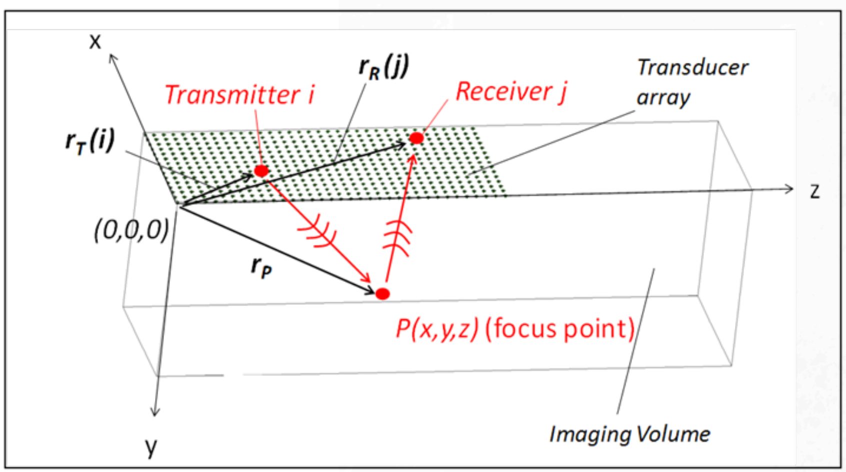


Image intensity at focus point P

\# receivers

\# transmitters

$$I(r_P)=\sum_{j=1}^{N}\sum_{i=1}^{M} y\left[t_P(i,j),i,j\right]$$

Time delay

$$t_P(i,j)=\frac{|r_P-r_T(i)|}{v_{L,S}}+\frac{|r_P-r_R(j)|}{v_{L,S}}$$

Velocity of Longitudinal Wave or Shear Wave (multi-mode detection)

Signal-to-Noise Ratio of Tomographic-SAF image

$$SNR=\sqrt{N\times M}$$

Benefits & Disadvantages

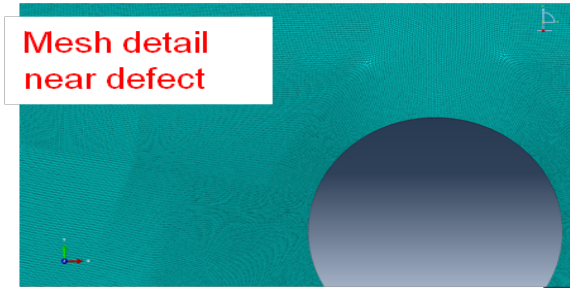
Benefits

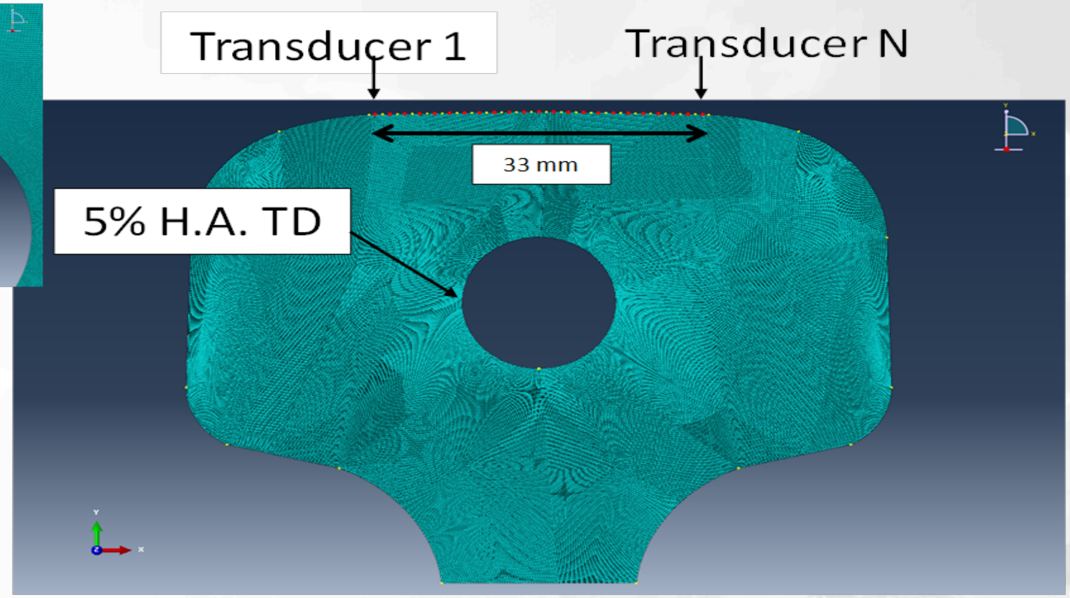
- Allows 3-D imaging by minimizing number of ultrasonic transmitters
- Low power and reduced multiplexing complexity will allow development of field-deployable prototype
- 3-D images generated automatically with little or no operator intervention

Disadvantages

- Requires multiple ultrasonic transmitters and receivers (ultrasonic array)
- Imaging algorithm must be efficiently designed for fast results (less than 3 minutes total inspection time desired)

2-D Rail Flaw Imaging



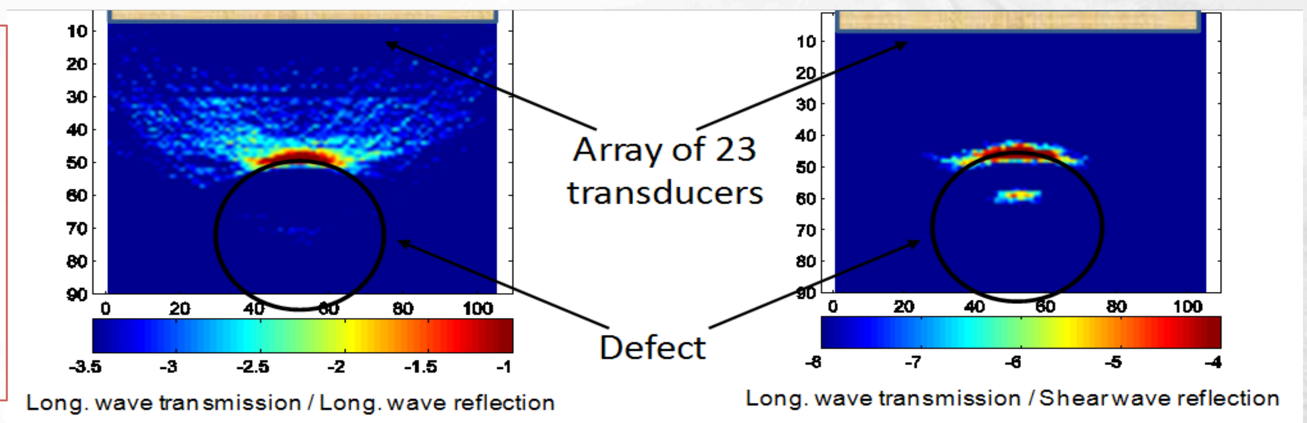


2-D Finite Element Analysis parameters:

- Total number of nodes: 188256
- Total number of elements: 187112
- Element type: linear quadrilateral (CPS4R)

[Movie 2-D imaging]

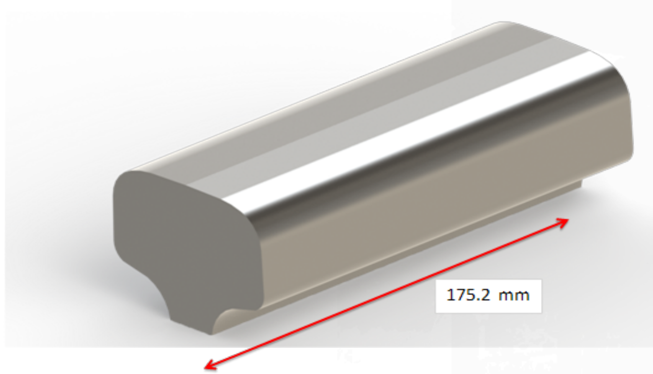
2-D imaging results with 25 dB artificial noise added to synthetic signals

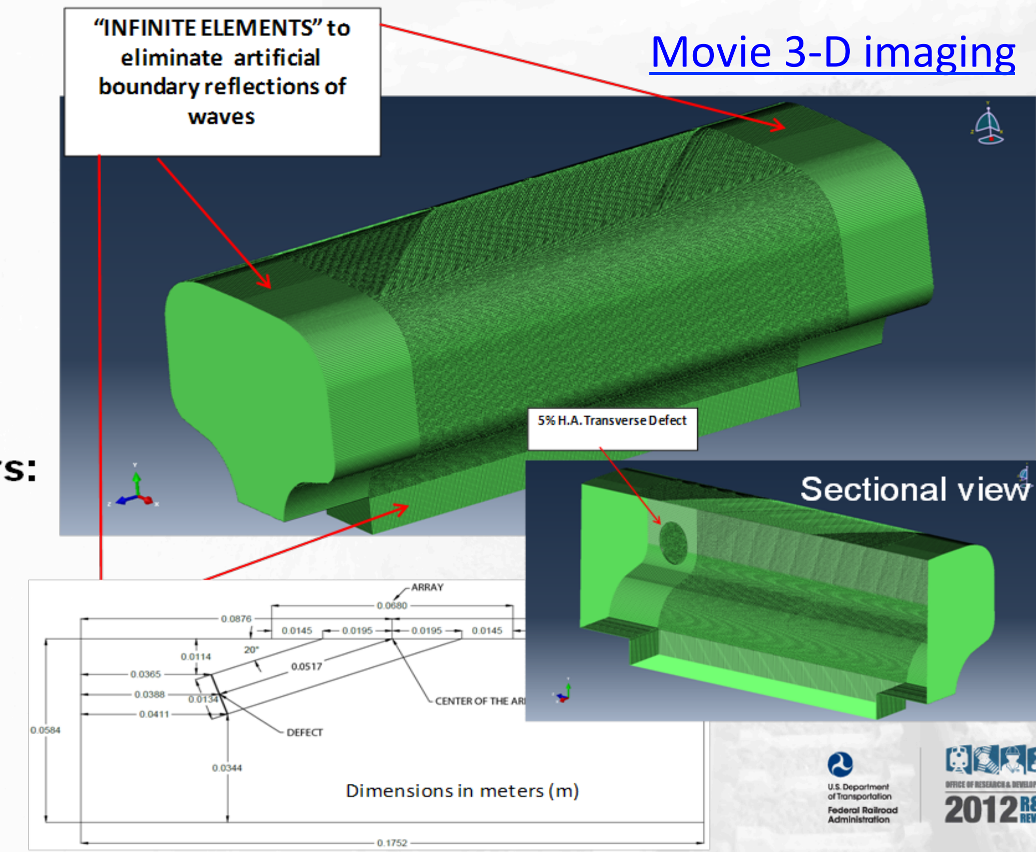


3-D Rail Flaw Imaging

- Developed 3-D FEA model of 136-lb rail with 5%H.A. Transverse Defect inclined at 20-deg from vertical direction (realistic orientation).
- Implemented "Infinite Elements" at model boundaries to avoid artificial wave reflections not existent in the field.

Movie 3-D imaging



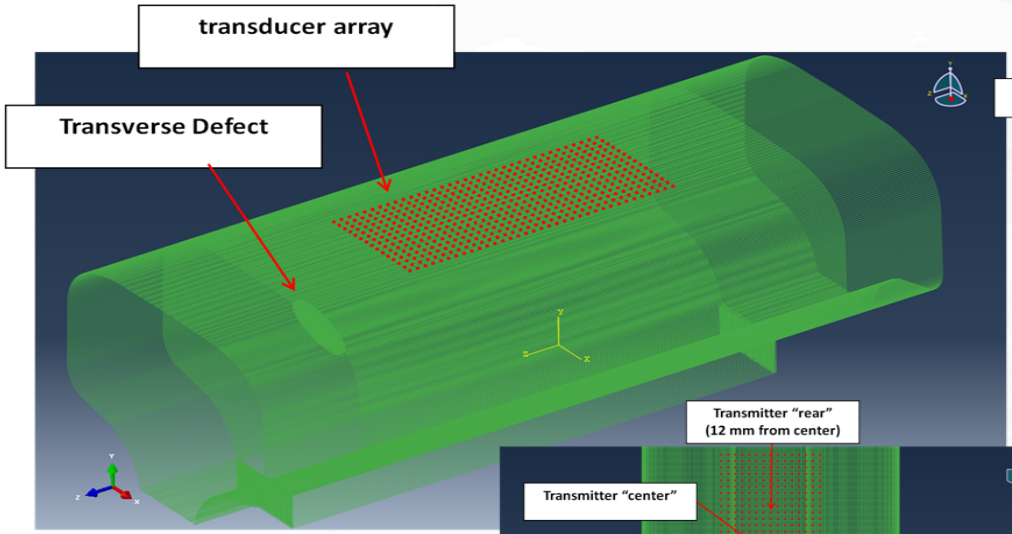


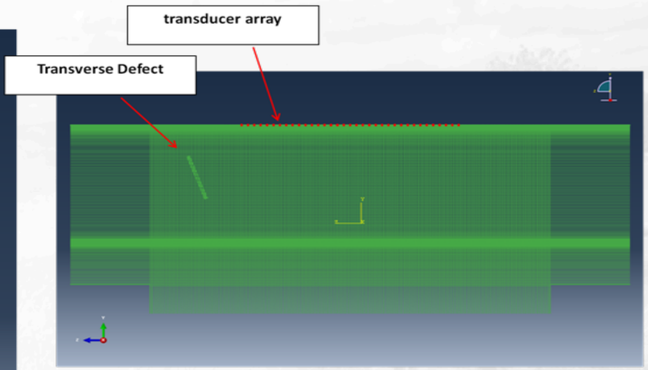
3-D Finite Element Analysis parameters:

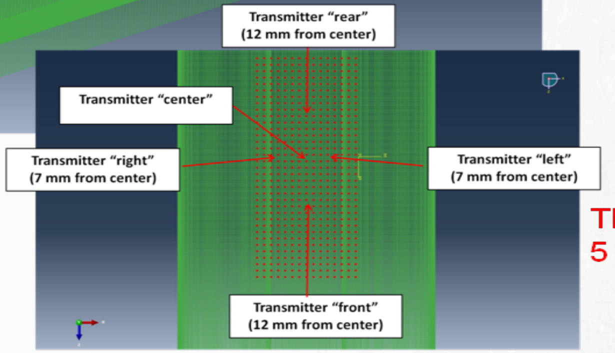
- Total number of nodes: 3,948,855
- Total number of elements: 4,023,918
- Element type: linear hexahedral (HEXA C3D8R)
- Elements at boundaries: "infinite" elements (HEXA CIN3D8)

3-D Rail Flaw Imaging
Synthetic Aperture Focusing (SAF) Array

- Simulated planar array of 525 transducers at 2mm spacing for Tomographic SAF
- Transmitters: used "sparse" configuration (5) to minimize # excitation channels
- Receivers: considered "Full Array" (all 525) and "Reduced Array" (only 140)

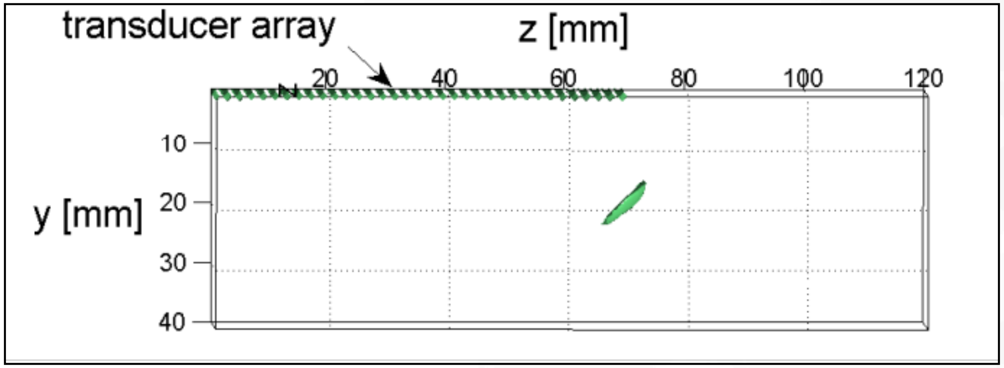


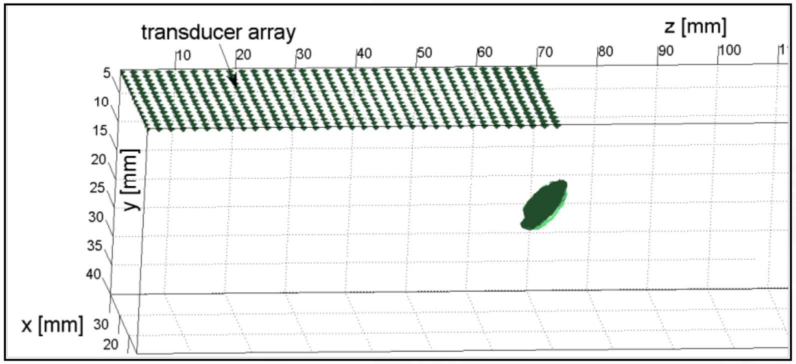


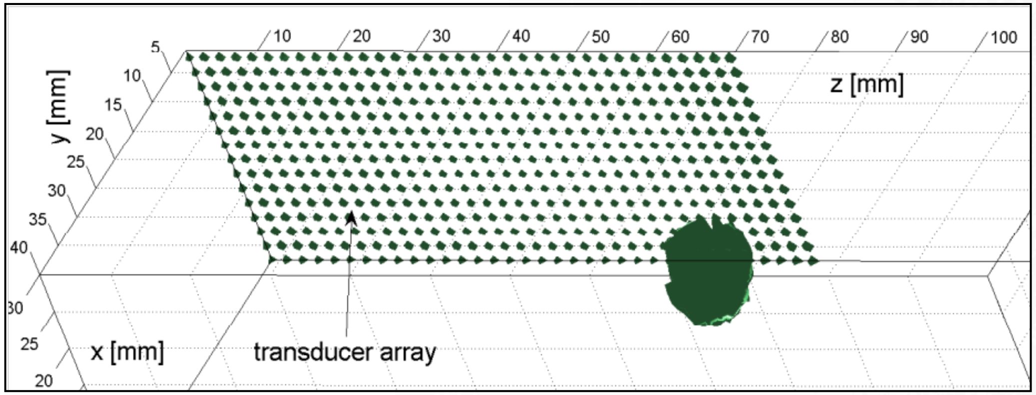


The "sparse" positions of the 5 transmitters in the array

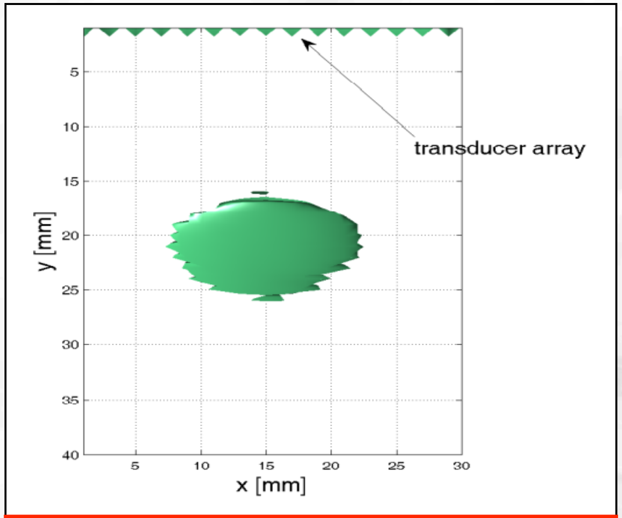
3-D Rail Flaw Imaging Results







Sparse Transmitter Array (5) - Full Receiver Array (525)
Longitudinal Mode and Shear Mode
Envelope baseline subtraction



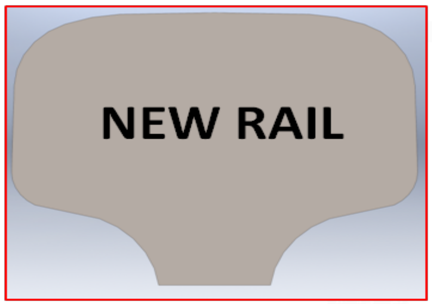
ACCURATE TRANSVERSE DEFECT SIZING

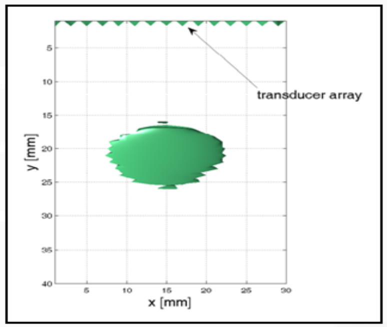
Actual defect size:
5.0% H.A.

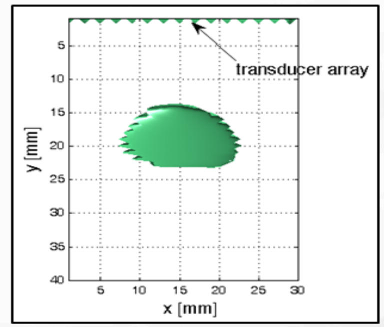
Defect size from imaging with full array:
5.3% H.A.

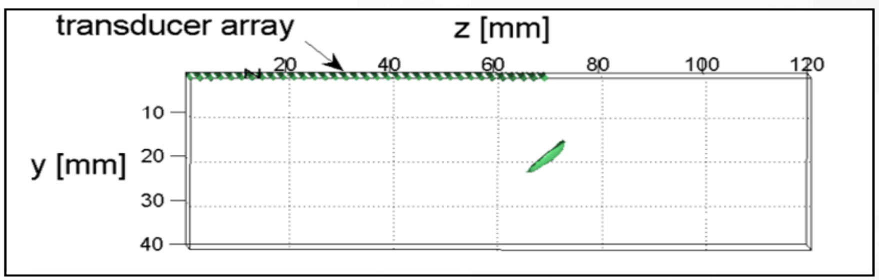
3-D Rail Flaw Imaging Results: New Rail Vs. Worn Rail

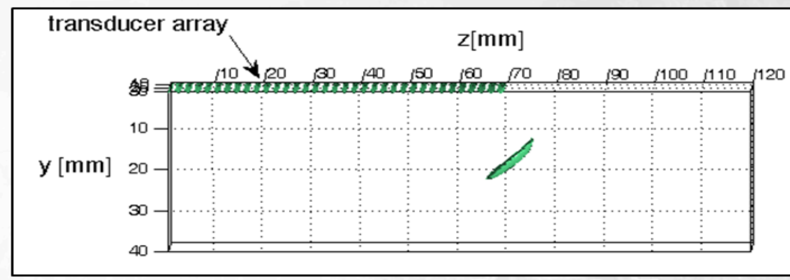
Sparse Transmitter Array (5) with Full Receiver Array (525)
Longitudinal Mode and Shear Mode. Envelope baseline subtraction.

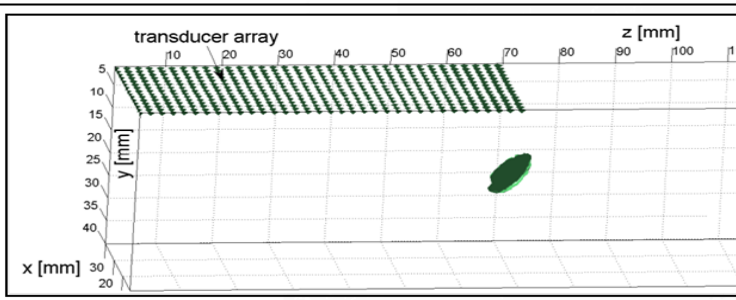


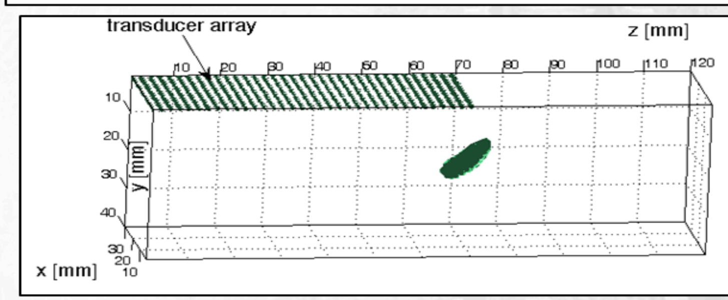












Summary of Results-to-Date

- Ultrasonic Tomography technology developed for 3-D imaging of internal rail flaws.
- Phase I work consisted of Finite Element Analyses simulating Ultrasonic Tomographic array on rail model, followed by Matlab© processing for defect imaging.
- Demonstrated successful 2-D and 3-D imaging of 5% H.A. Transverse Defect in 136-lb rail with <u>excellent defect sizing estimation</u>.
- 3-D imaging results obtained with only 5 transmitters and as few as 140 receivers without need for moving the array (further reductions possible).
- "New rail" vs. "Worn rail" results:
  - Full receiver array (525) shows no degradation of 5% H.A. TD image.
  - Reduced receiver array (140) shows some degradation of 5% H.A. TD image; results could be improved by better selection of transducer positions in reduced array.
  - Theoretically, any effect of wear would be eliminated if actual transducer positions on worn rail were considered in image reconstruction algorithm.