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The Imminent Ultrasonic Guided Wave Revolution in SHM

Ben Franklin Center of Excellence in Structural Health Monitoring Inaugural Meeting
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Organization

- Fundamentals
- Aircraft
- Pipeline
- Rail
- Conclusions

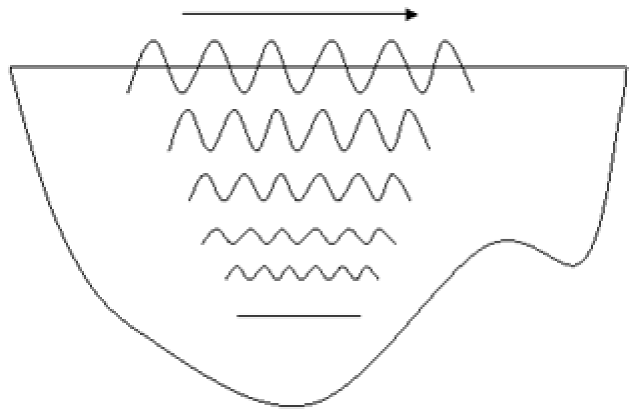
Why?

- Superb benefits of guided inspection including speed and cost.
- Tremendous advance in understanding of guided waves today.
- Computational facilities that are available today.
- The number of critical infrastructure problems facing us today
  - Aircraft
  - Pipeline
  - Rail
  - Bridges
  - Buildings
  - Pressure vessels
- Fun to have complexity become a benefit

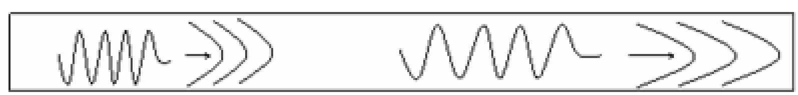
Natural Waveguides

- Plates (aircraft skin)
- Rods (cylindrical, square, rail, etc.)
- Hollow cylinder (pipes, tubing)
- Multi-layer structures
- Curved or flat surfaces on a half-space
- Layer or multiple layers on a half-space
- An interface

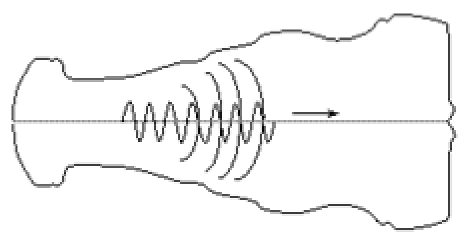
Guided Wave Possibilities



a). Rayleigh (surface) wave schematic



b). Lamb wave schematic

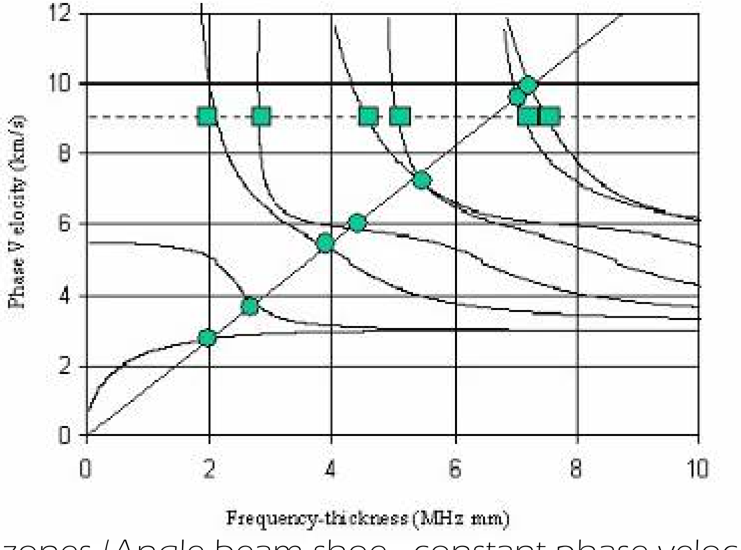


c). Stonely wave schematic

Lamb Wave Mode Activation Possibilities


a). angle beam probe


b). comb probe



c). Mode excitation zones (Angle beam shoe—constant phase velocity [horizontal line] determined from Snell's Law for a given angle. Comb transducer excites modes with a constant wavelength [sloped line] determined by the spacing of the elements.)

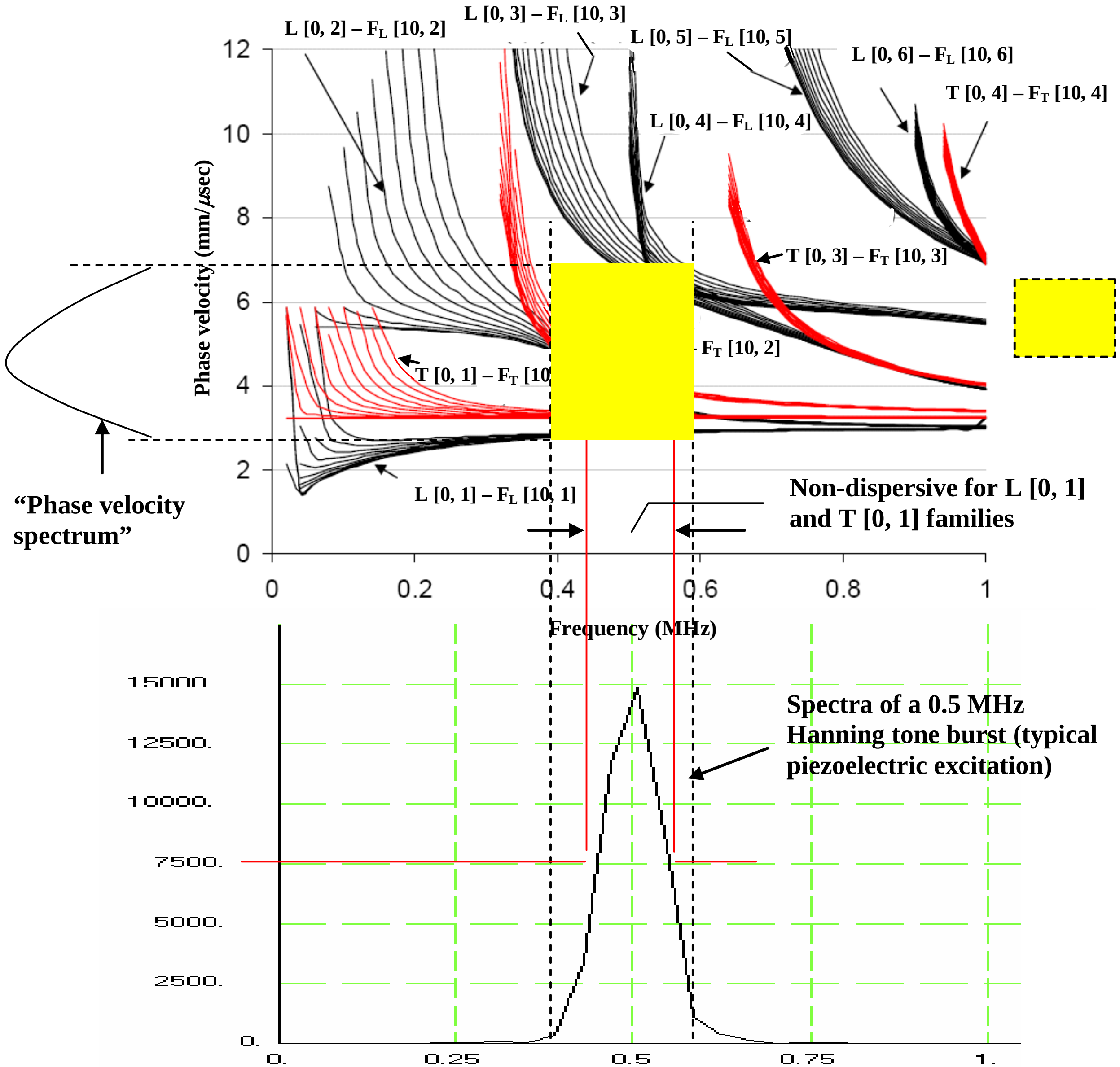


Figure 3

Illustration of the concept of a phase velocity spectrum. The "source," is a piezoelectricially generated, 500 kHz pulse. Modes within the yellow shaded activation zone can be generated. Normally though, only the L [0, 1], T [0, 1], and the L [0, 2] modes are very evident with flexural modes typically not being propagated but can occur as a result of reflection from a non-symmetric reflector within a pipe wall

Benefits of Guided Waves

- Inspection over long distances from a single probe position.
- Often greater sensitivity than that obtained in standard normal beam ultrasonic inspection or other NDT techniques.
- Ability to inspect hidden structures and structures under water, coatings, insulations, soil, and concrete.
- Cost effectiveness because of inspection simplicity and speed.
- Beam focusing potential for improved probability of detection, reduced false alarm rate, penetration power and inspection confidence.
- Excellent overall defect circumferential and depth sizing potential.

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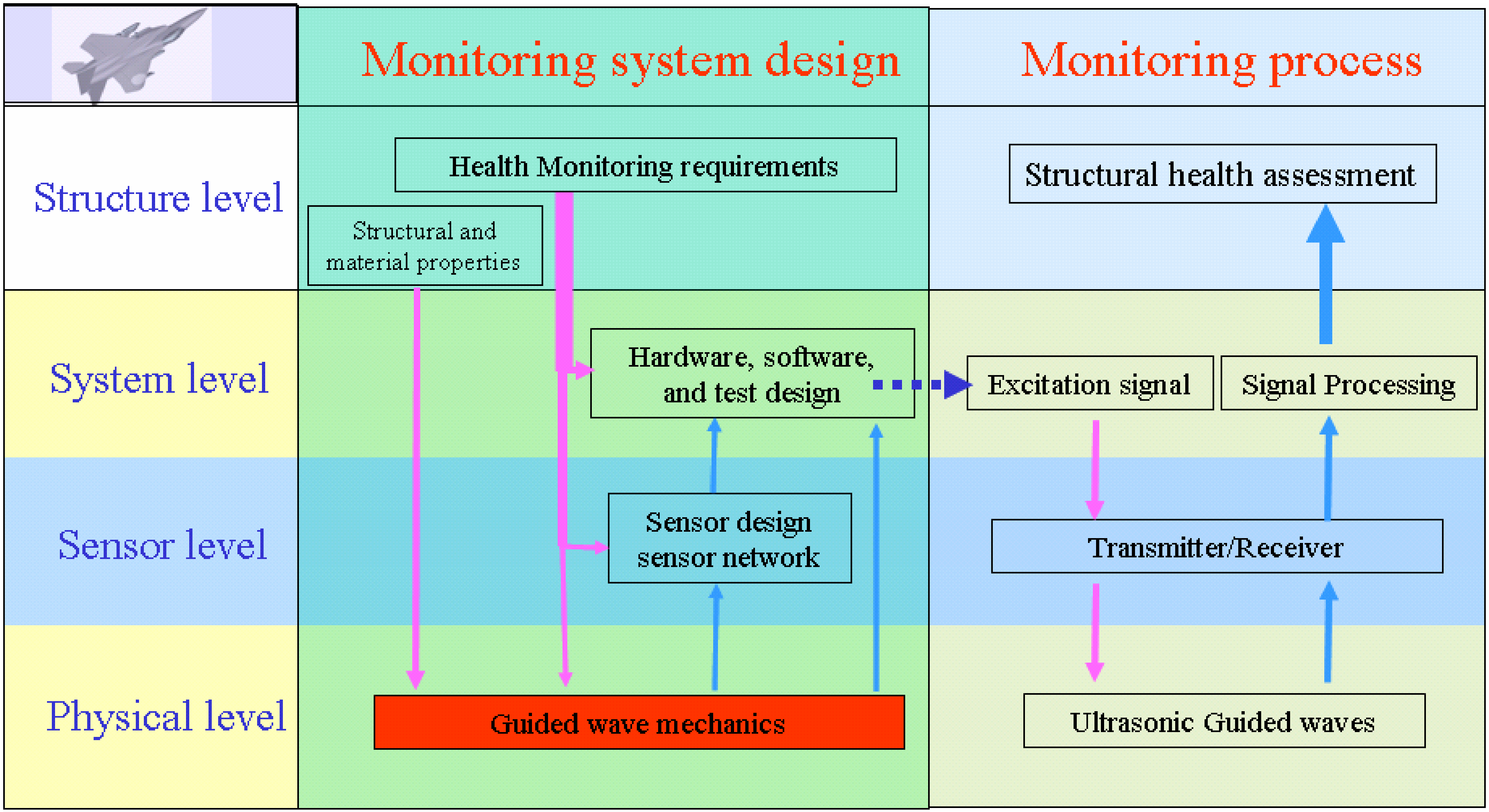
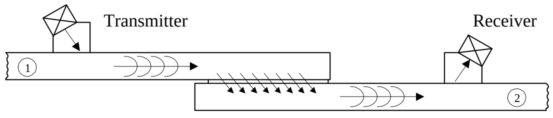
A vision of a "Theoretically-driven structural health monitoring " strategy



A Lap Splice Inspection Sample Problem



a). Ultrasonic through-transmission approach for Lap Splice joint inspection

b). Double spring “hopping probe” used for the inspection of a Lap Splice joint

Taken from “Ultrasonic Guided Waves for the Detection of Anomalies in Aircraft Components”, J. L. Rose, L. Soley, Material Evaluation, Vol. 50, No. 9, Pg 1080-1086, 2000.

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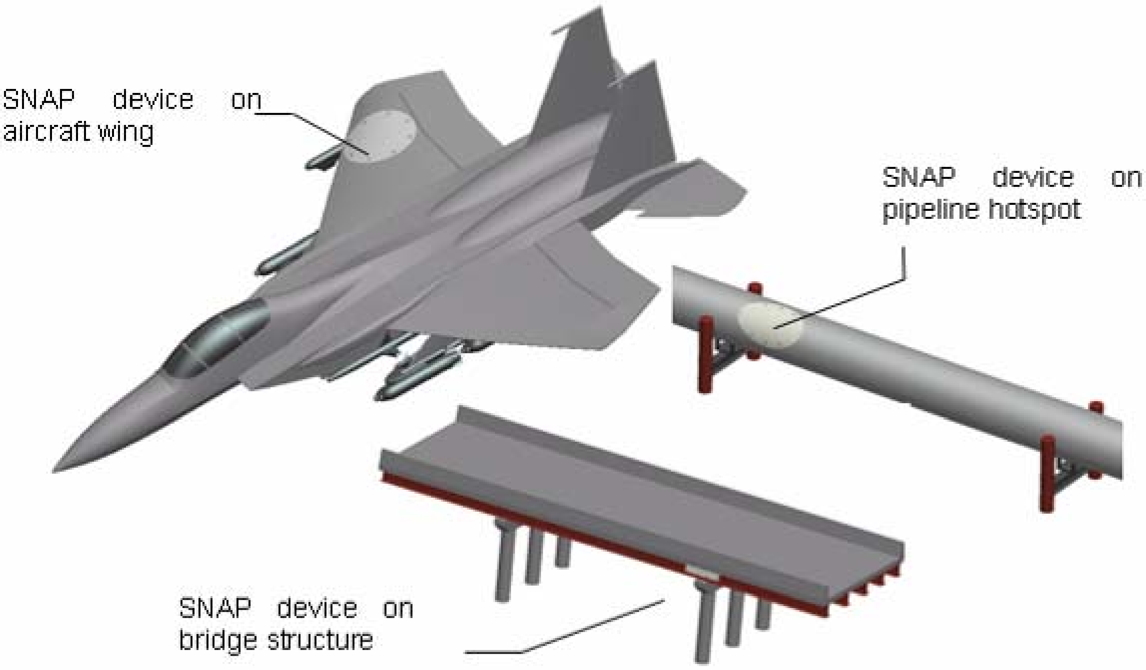
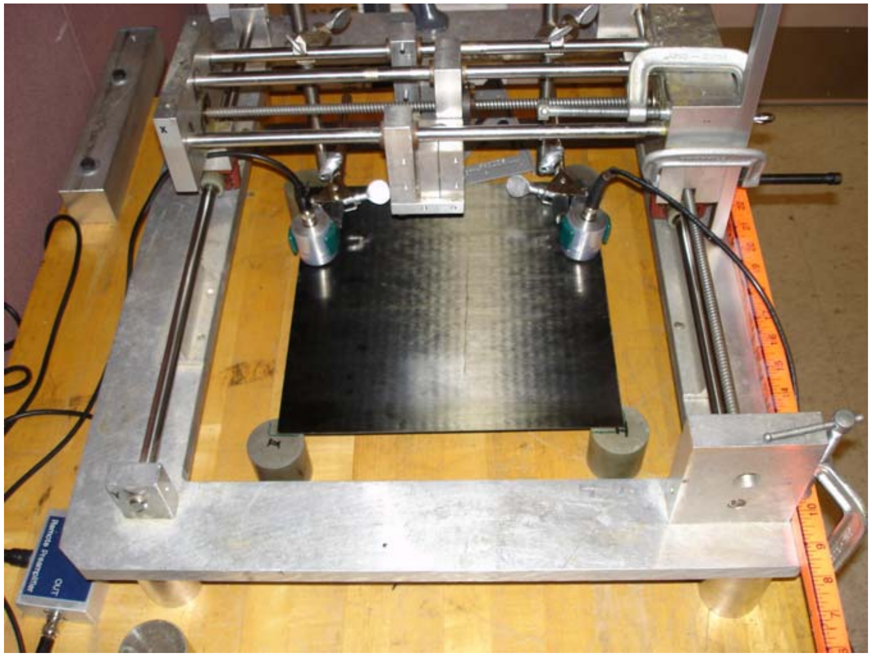
Artist conception of sensor network acoustic patch (SNAP) device application

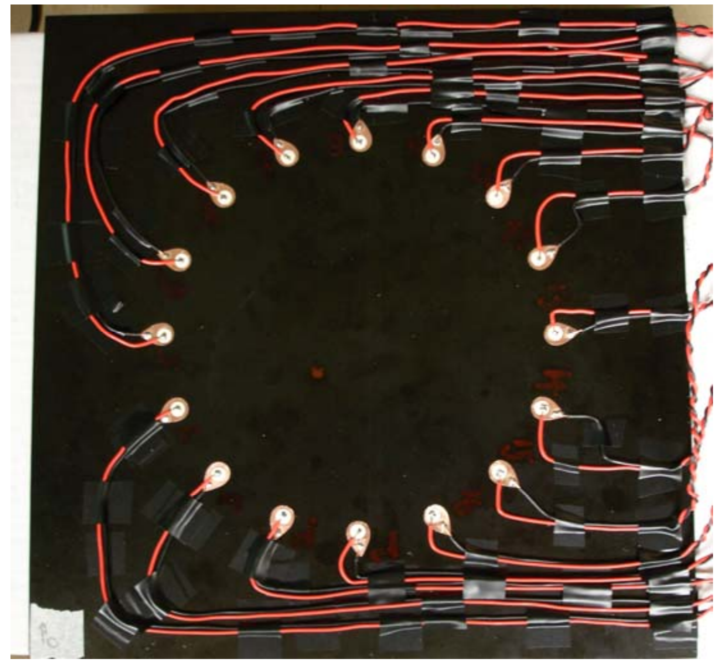


Fiber Reinforced Composite Plate Inspection

Air coupled sensors used for guided wave tomography scan



Leave-in-place sensor array for Structural Health Monitoring (SHM)



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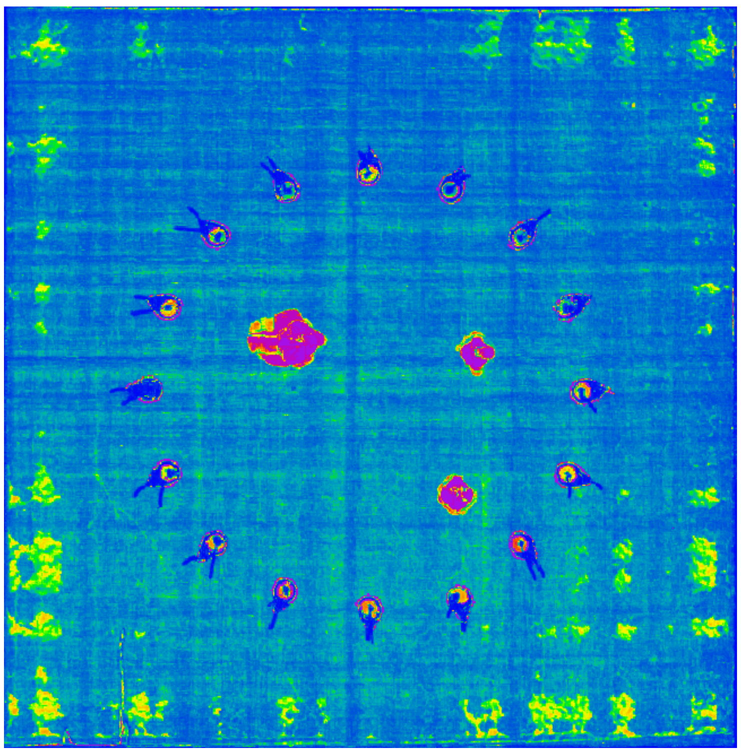
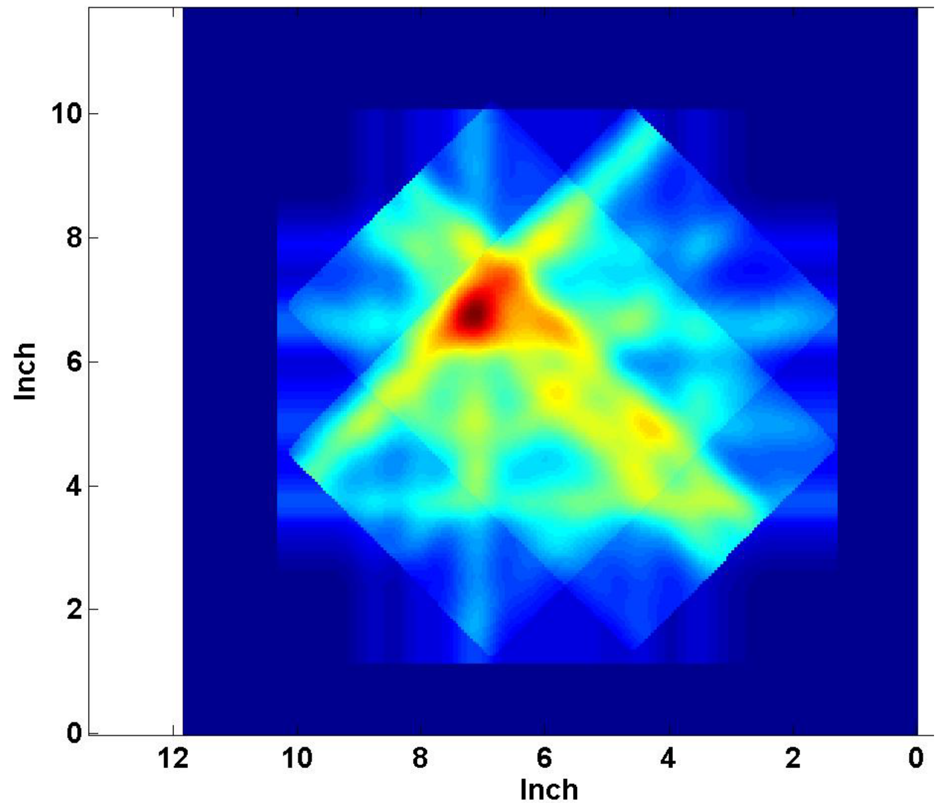
Feature Based Systems

Air Coupled Inspection of Impact Delaminations in an Orthotropic Plate

C-scan



Lamb Wave Scan



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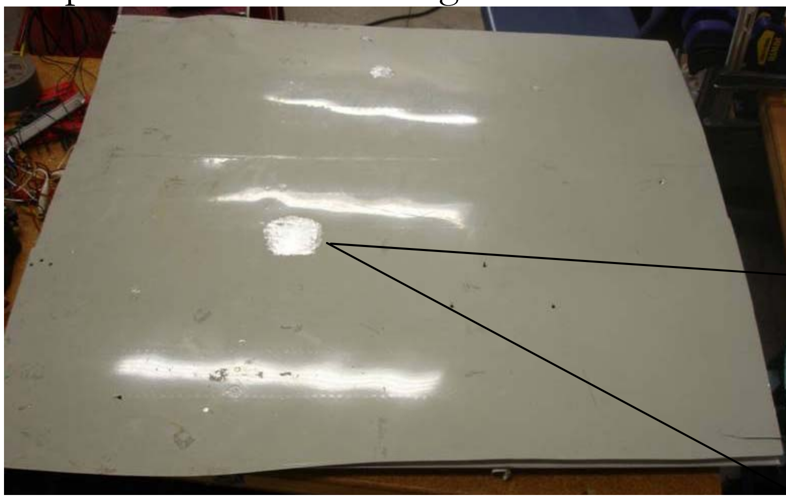
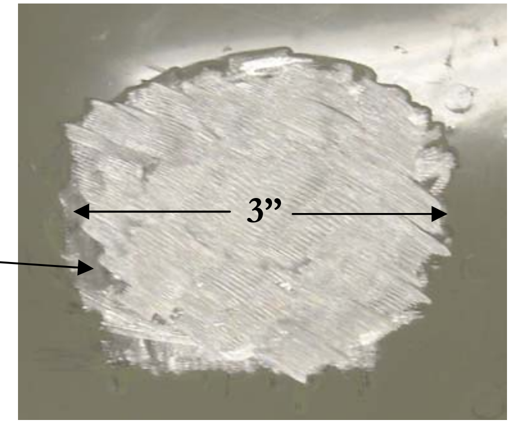
Simulated Corrosion Detection on an Aluminum Plane Wing

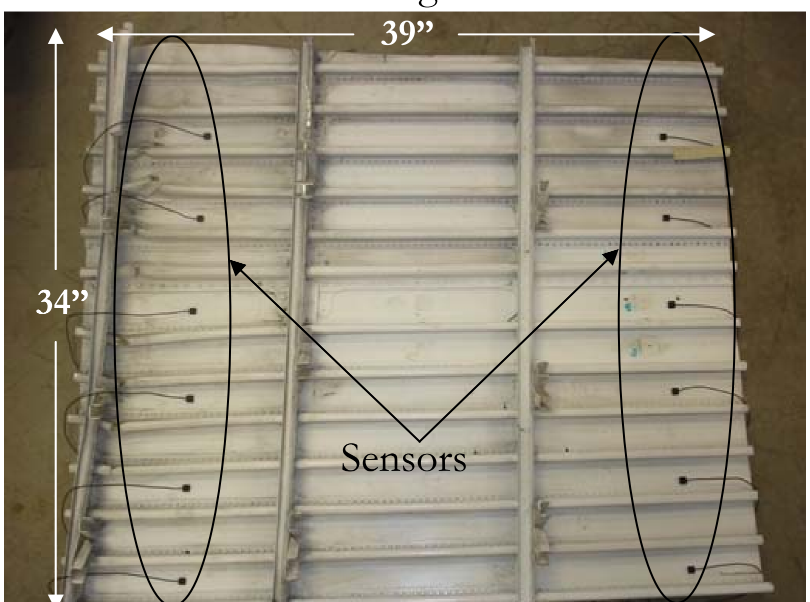
"Exposed" surface showing simulated corrosion defect



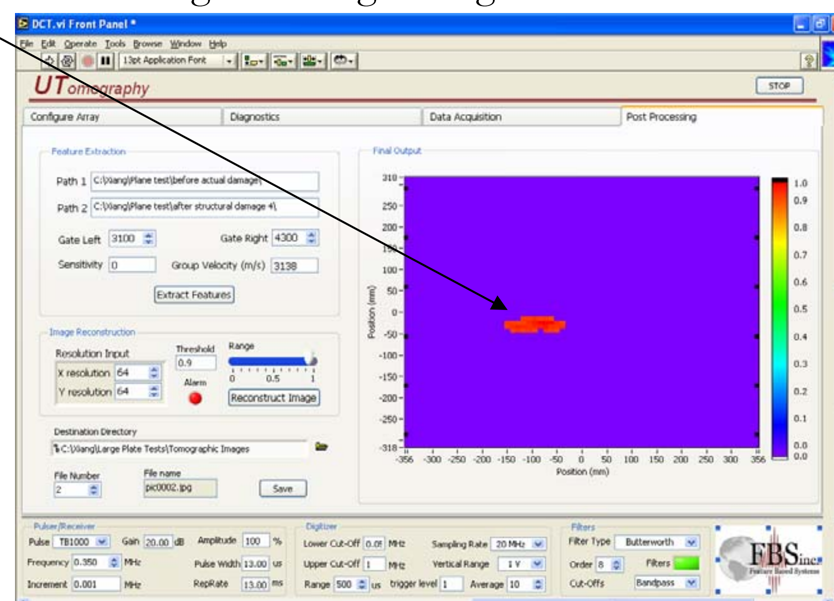
Defect

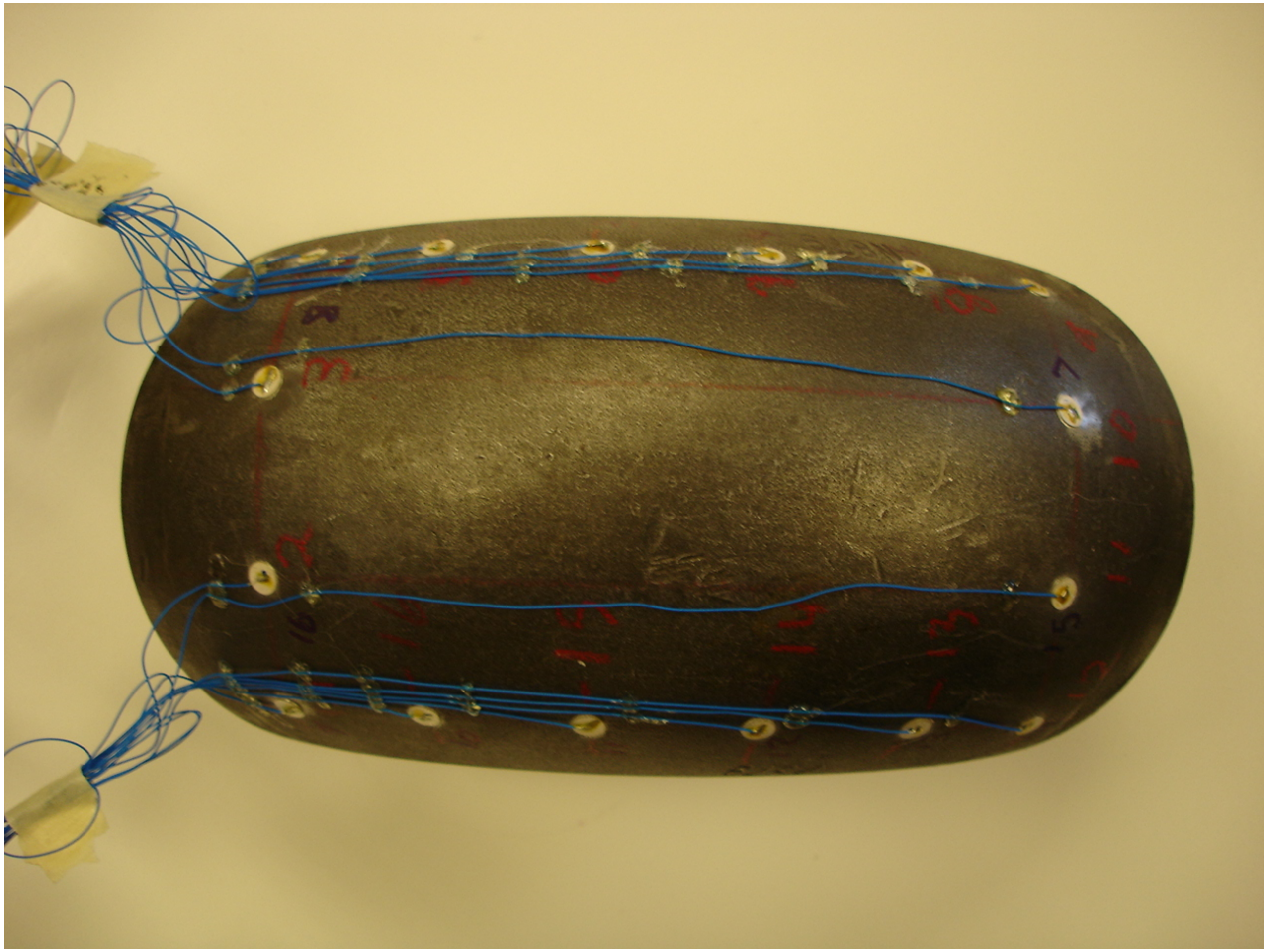


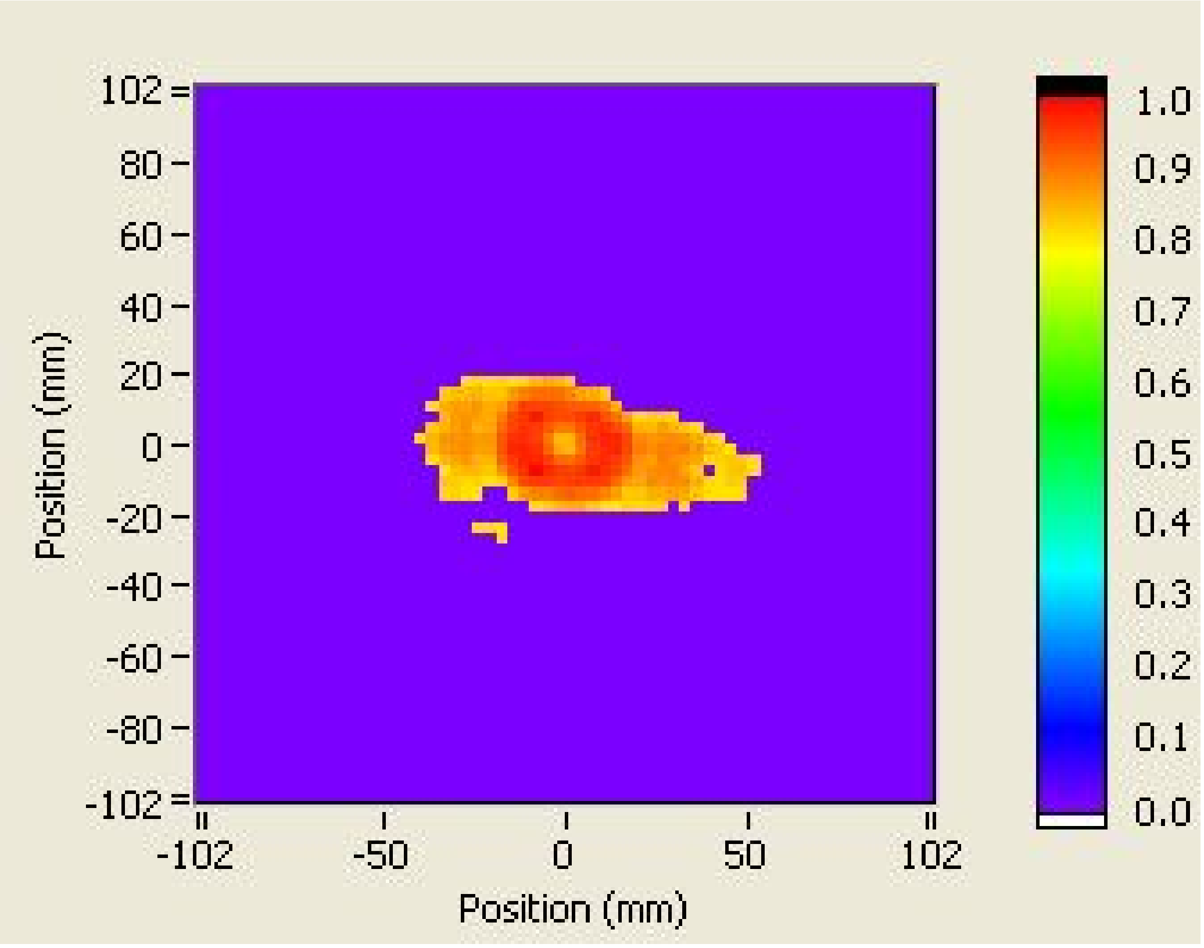
"Hidden" surface showing embedded sensor array



CT Image showing damage location and size

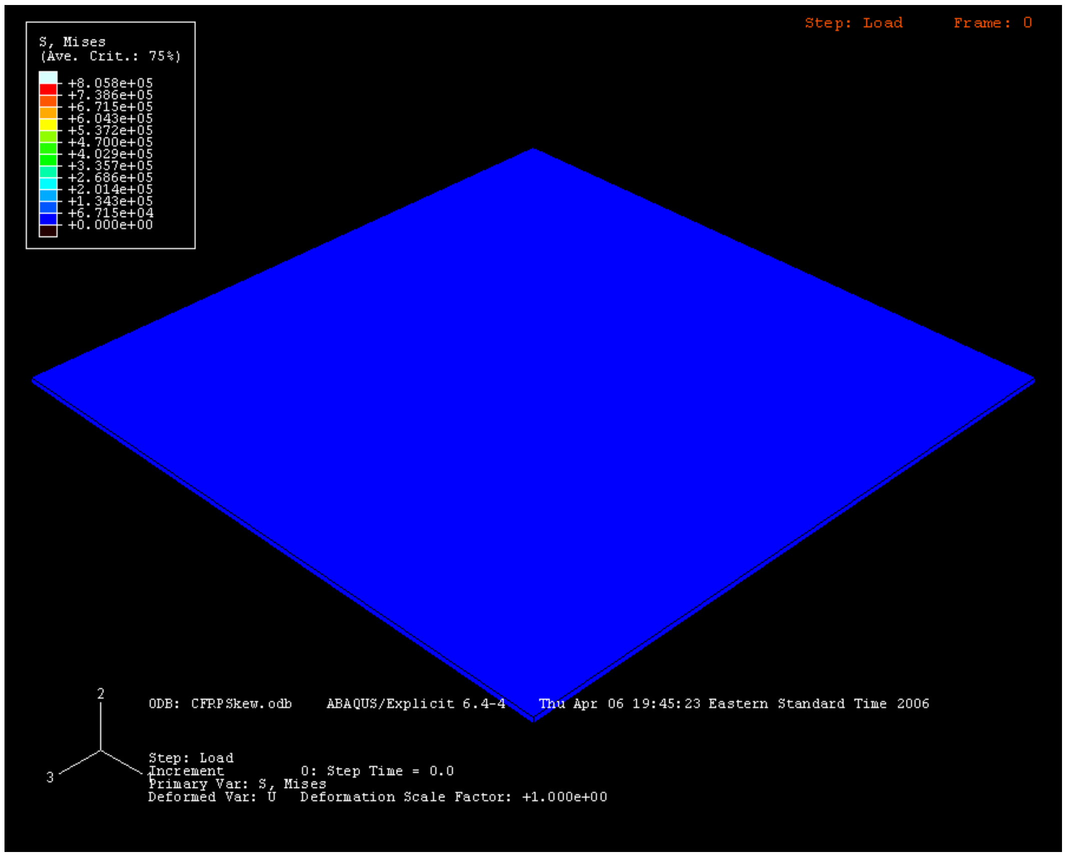




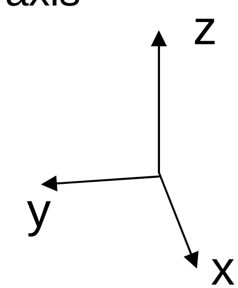

102
80
60
40
20
0
-20
-40
-60
-80
-102
Position (mm)
-102
-50
0
50
102
Position (mm)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

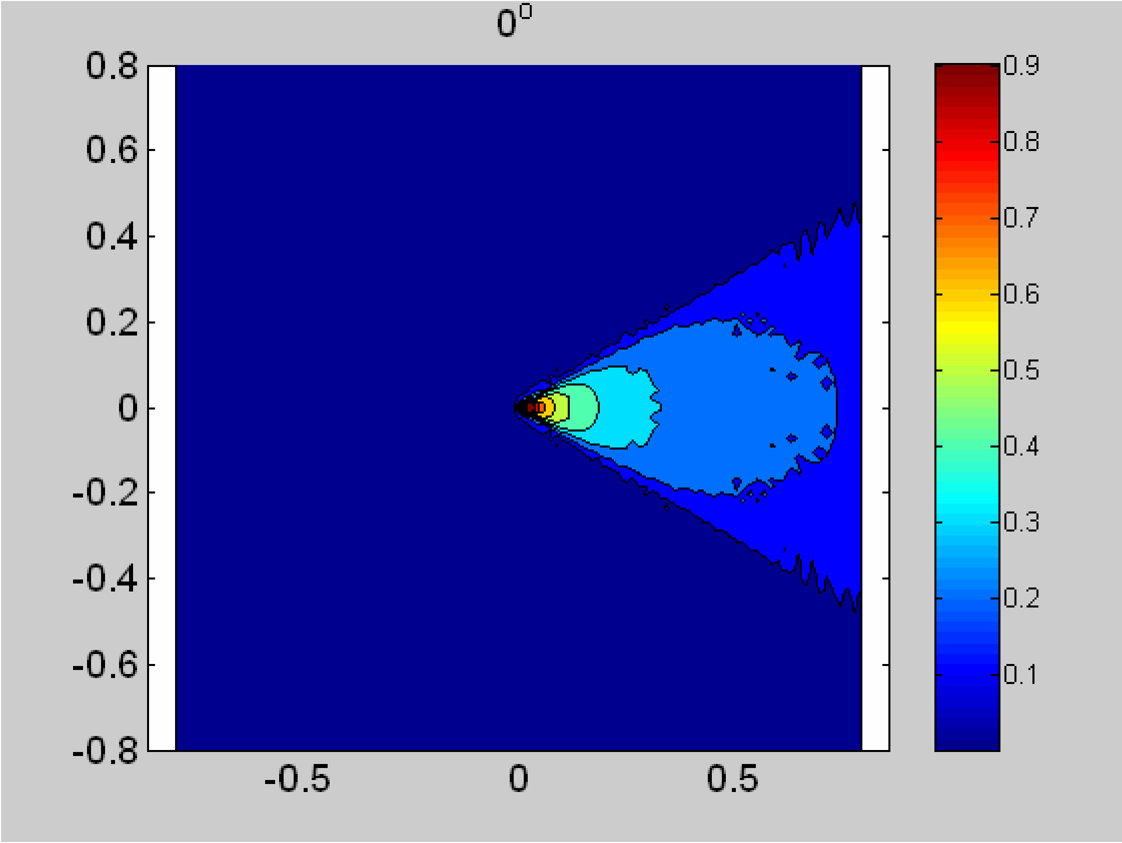
Lamb Wave in Anisotropic Plate

- Skew angle for the second symmetric mode at *fd*=1.05 MHz-mm

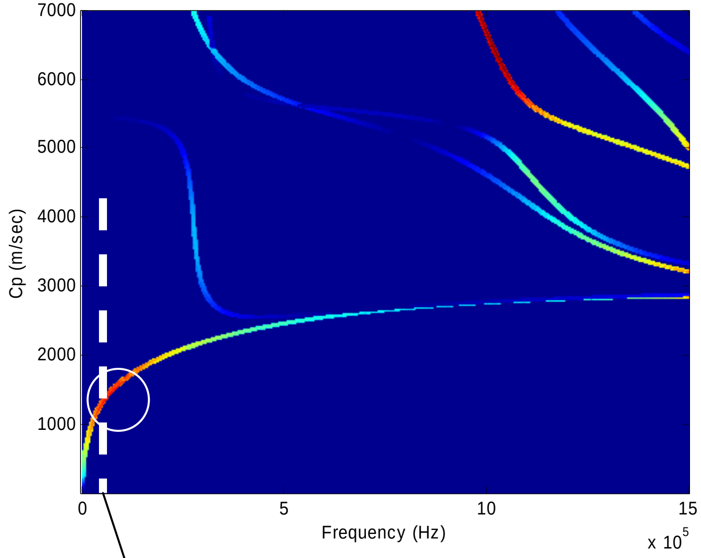


Crystallographic axis




0°
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-0.5
0
0.5
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

Proof of ISCC Concept with High Energy Transducer



Use high energy transducer around 50 kHz to generate high interface shear stress, hence to de-ice.

f=52khz

Guided Wave Pipe Focusing Techniques

- Frequency tuning

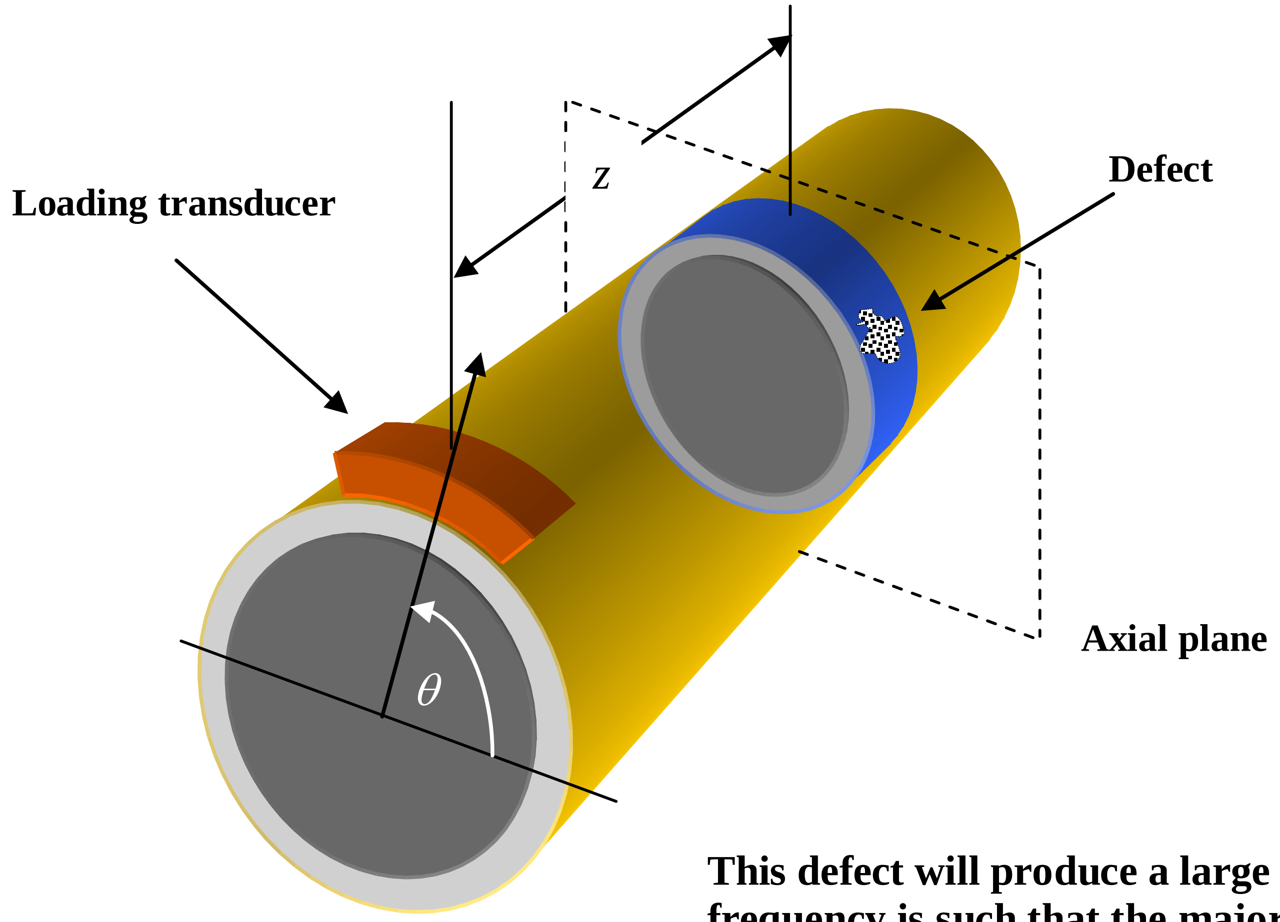
  axisymmetric excitation and receiving

- **Natural focusing**

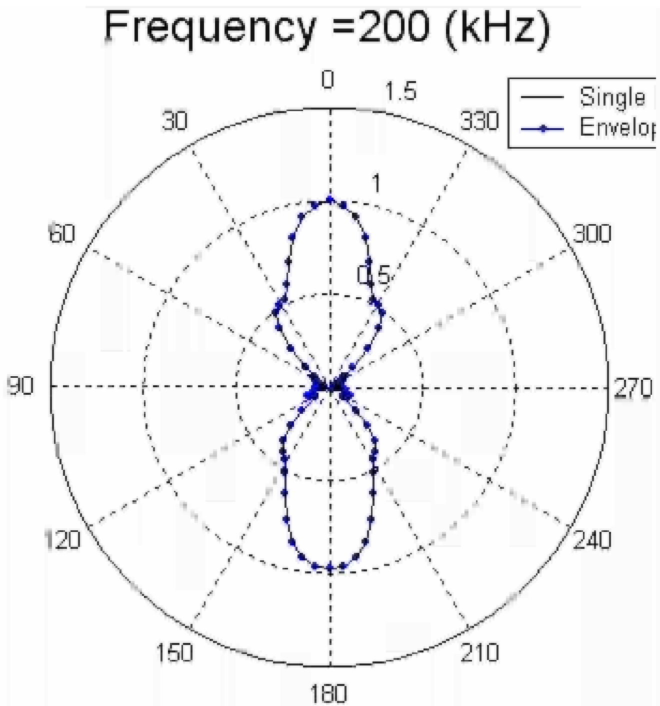
  partial loading excitation and receiving

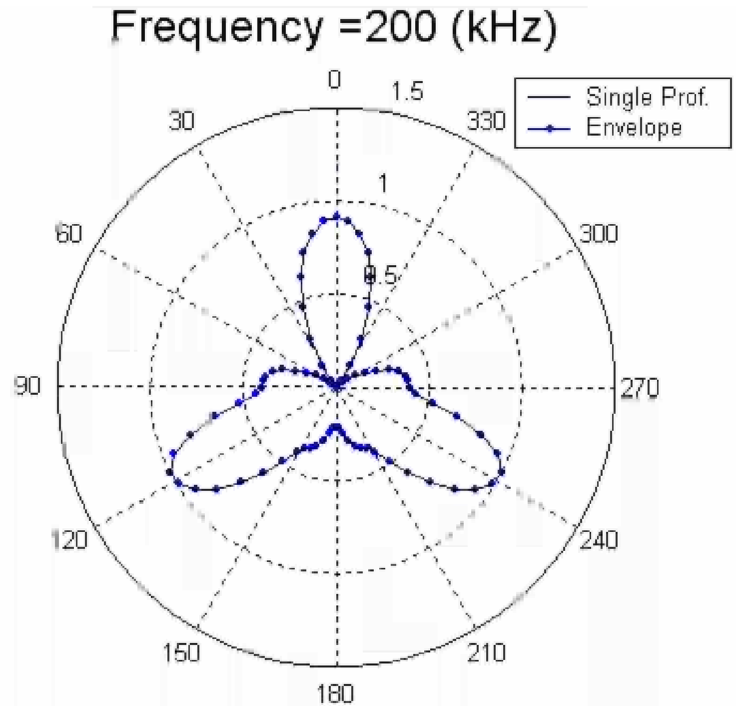
- Phased array focusing

  multi-element array excitation and receiving with time delay and amplitude tuning



This defect will produce a large response if the frequency is such that the major lobe of the displacement profile is located near or on it.



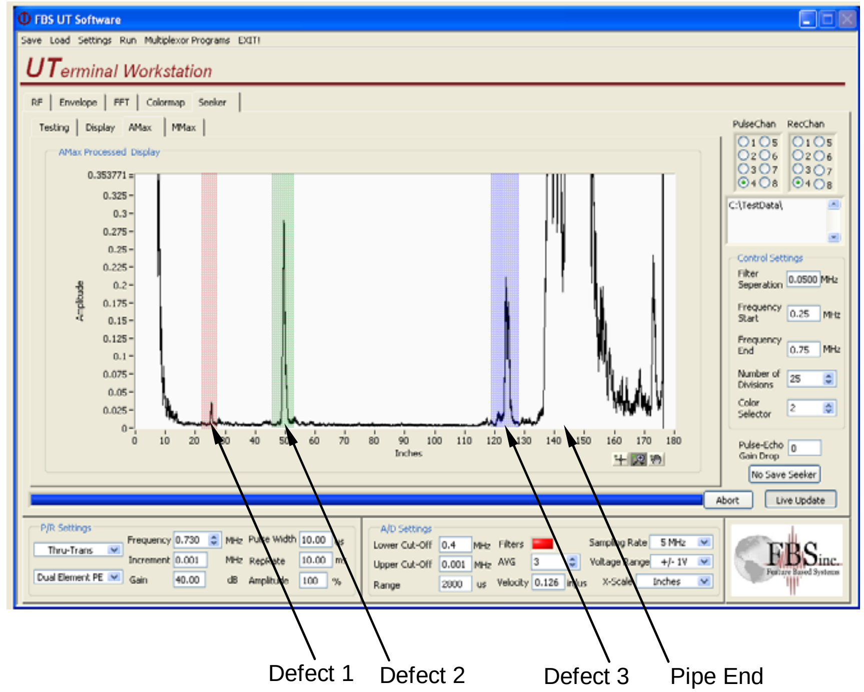


Sample T(0,1) and L(0,1) mode group excitation for a 4” Schedule 40 pipe (movies)

(Longitudinal and Torsional envelope of single element profile with frequency tuning from 200kHz to 800kHz at z=15’ (180”))

The FAT Technique

- Waveforms are produced by utilizing 8 different circumferential angle locations and frequencies over the range 250 kHz to 750 kHz, hence FAT, Frequency and Angle Tuning.



Defect 1: 0.36% Cross Sectional Area (CSA) internal simulated corrosion, 24” from end

Defect 2: 0.64% CSA external simulated corrosion, 48” from end

Defect 3: 1.18% CSA external simulated corrosion, 120” from end

5 (a) FAT result from 3 defects in a 4” Schedule 40 steel pipe

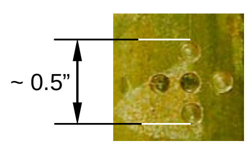


Image of Defect 3:
50% through wall
0.125” dia. holes

5 (b) Photograph of one of the defects used for FAT experiment

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Guided Wave Pipe Focusing Techniques

- Frequency tuning

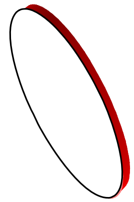
  axisymmetric excitation and receiving

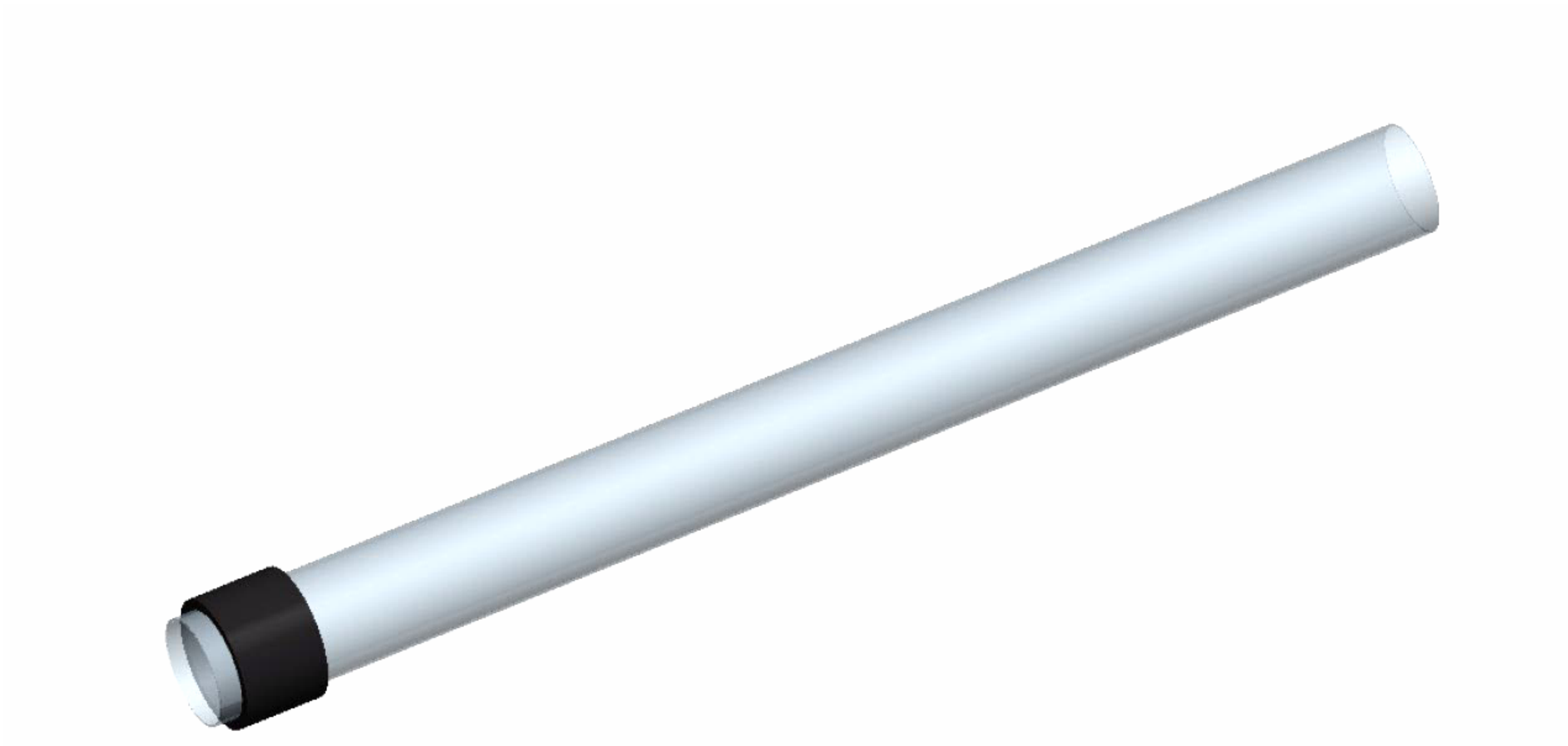
- Natural focusing

  partial loading excitation and receiving

- **Phased array focusing**

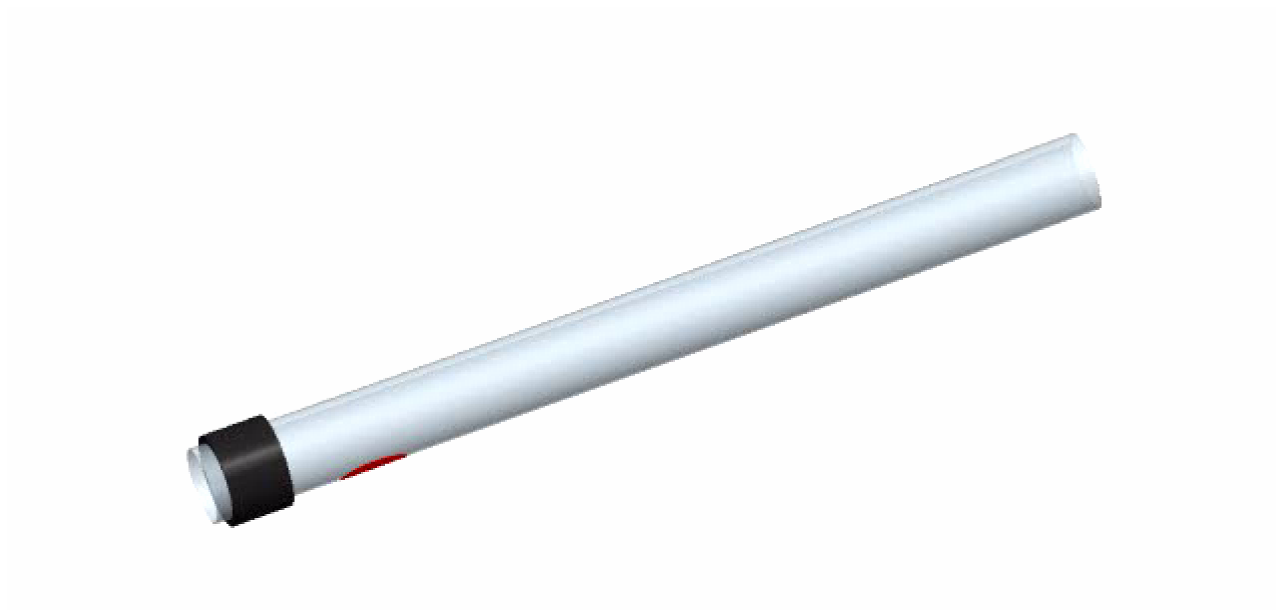
  multi-element array excitation and receiving with time delay and amplitude tuning

 = Propagating ultrasonic wave



Axisymmetric loading producing axisymmetric wave propagation

= Focal zone



Computer controlled variation of phased array element excitation times and amplitudes produces a moving focal zone covering the entirety of the pipe wall

Principal benefits of phased-array focusing for pipe inspection

1	Improved defect probability of detection (greater than 3% cross sectional area (CSA) for focusing, compared to more than 9% CSA for axisymmetric)
2	Decreased defect false alarm rate
3	Increased inspection confidence
4	Excellent defect circumferential location analysis
5	Improved signal to noise ratio compared to axisymmetric
6	Six to infinite dB defect signal improvement compared to axisymmetric
7	Increased penetration power in a coated pipeline with high attenuation
8	Potential characterization and defect sizing
9	Ability to determine circumferential profile of value in reflector characterization

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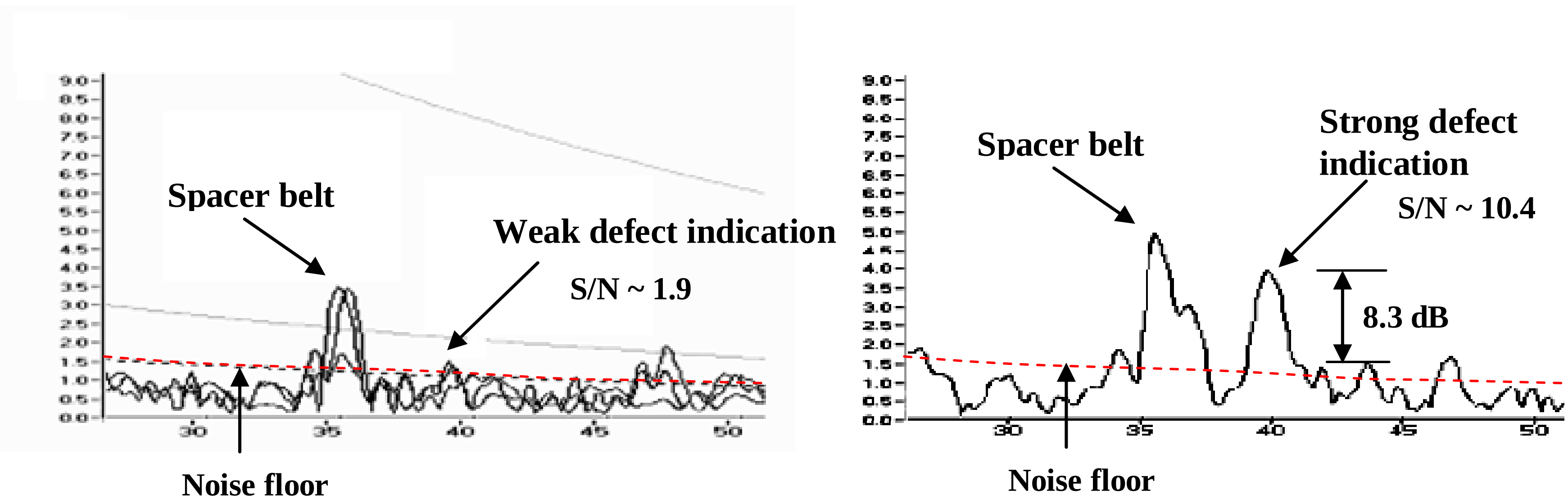


Figure 6

Data acquired from a 12 in. (0.3048 *m*) diameter coal tar coated pipe. Note that focusing provided a 8.3 dB enhancement of the defect echo and a ~ 9 dB gain in S/N ratio.

Principal benefits of using both torsional and longitudinal modes for pipe inspection

1.	Each of the modes has a different sensitivity to particular types of defects
2.	Each of the modes has a different penetration power with respect to different coating types
3.	Regarding penetration power when a pipe is liquid filled, the torsional mode in general would be better although specific longitudinal modes and frequencies would also work well
4.	Redundancy is a major benefit increasing the overall probability of detection significantly
5.	Mode conversion at a defect can be a combination of longitudinal and torsional modes despite impingement by only one mode

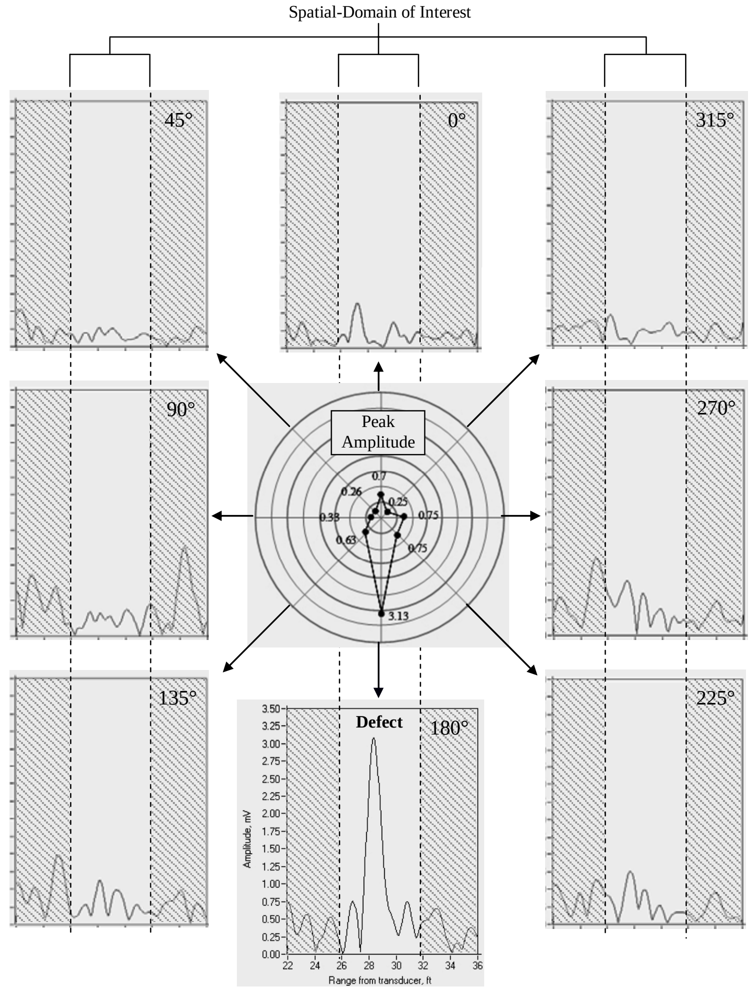


Figure 8

An example illustrating the circumferential defect-locating ability of the ultrasonic guided-wave phased-array focusing technique. In this example guided-wave energy is focused at 8 different angles at an axial distance of 9.14 m (30.0 ft). A sharp peak in reflected energy indicates that there is a defect located in the bottom octant (180°), at a distance 8.84 m (29.0 ft) from the location of the guided-wave inspection tool. Data was taken on a 0.4 m (16.0 in) diameter coated pipe.

Circumferential Locations and Sizing

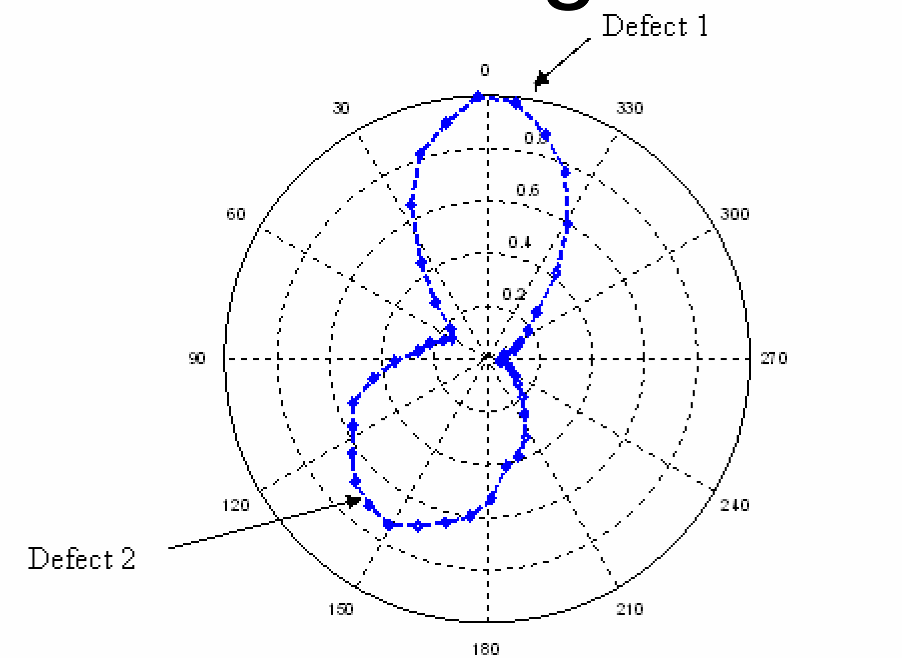
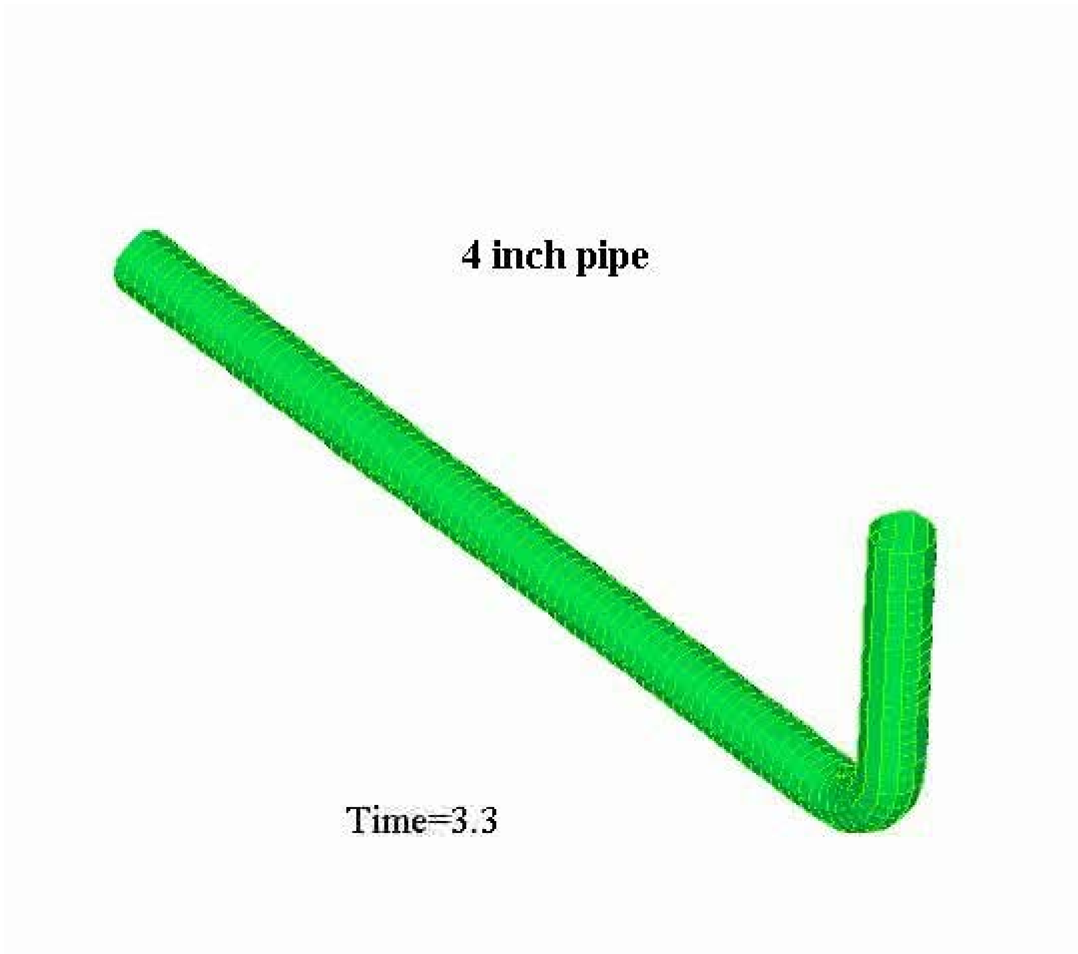
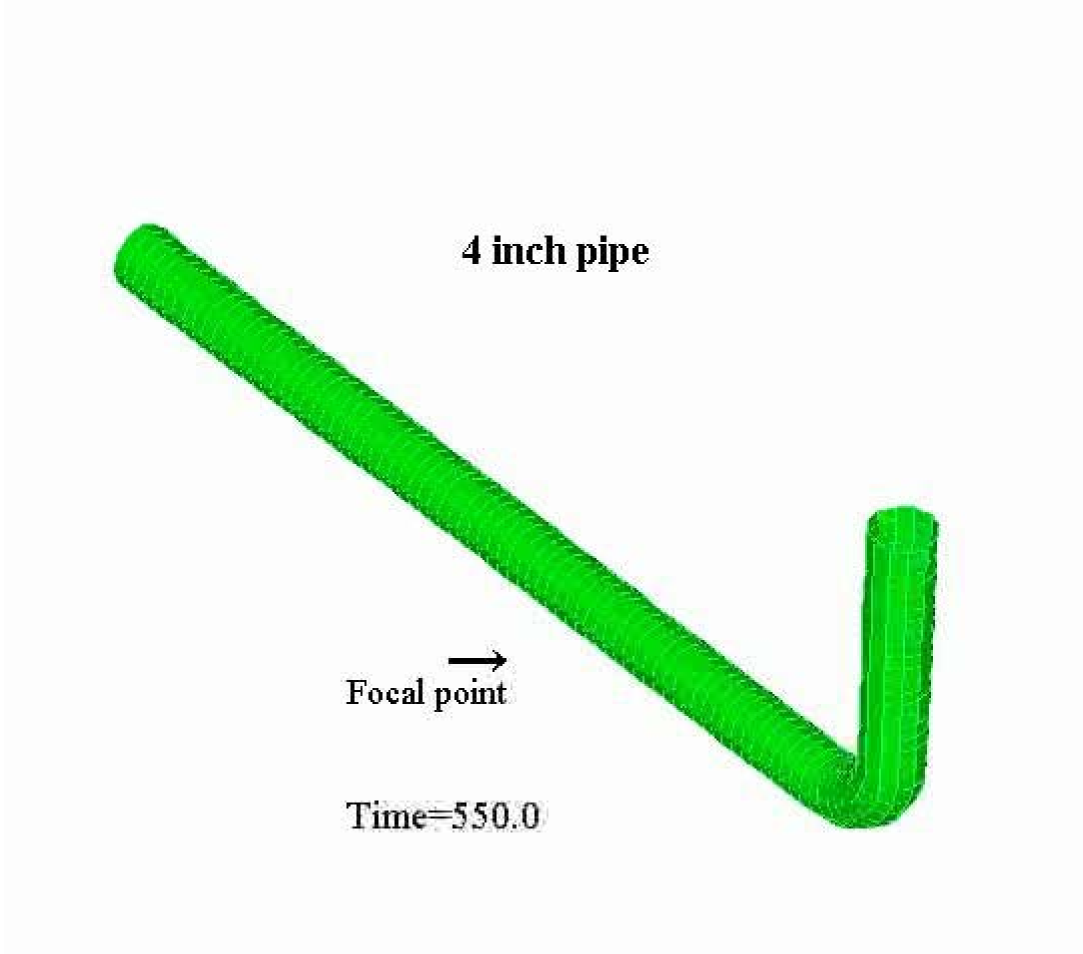


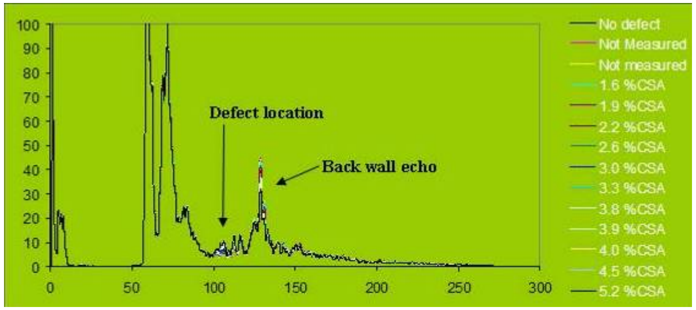
Figure 6. Maximum reflected echoes within the distance range: 12.5ft~20.8ft by applying 16-channel phased-array focusing. Circumferential length of each excitation channel is 22.5°. 35kHz T(0,1) wave group is focused at 15.4ft and 44 different circumferential locations.


4 inch pipe
Time=3.3

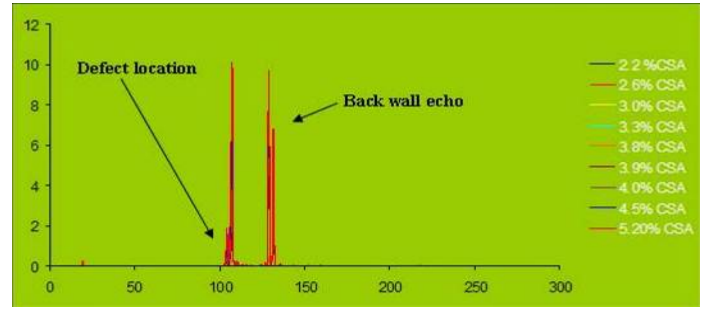

4 inch pipe
Focal point
Time=550.0

0-5% Elbow Structural Health Monitoring

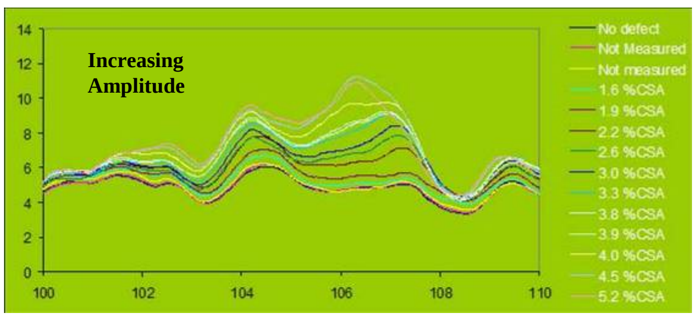
Max Plot of Entire Signal



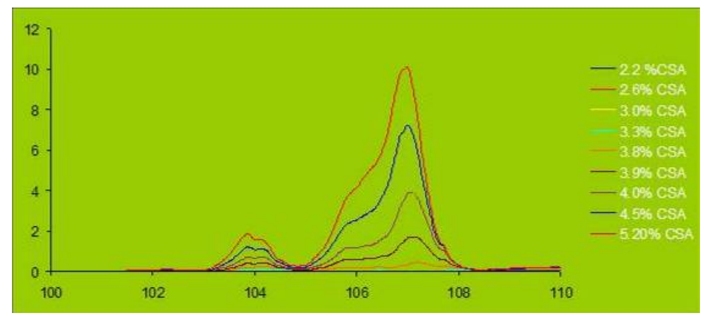
Dissimilarity Plot of Entire Signal



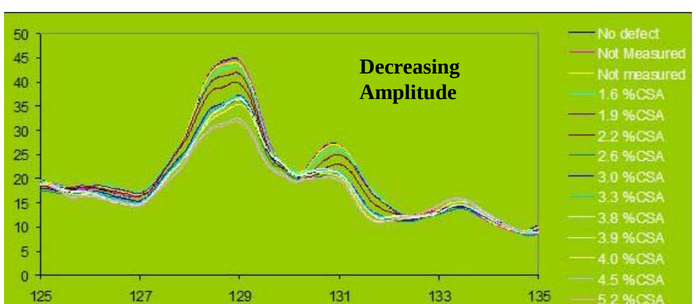
Max Plot of Defect Region



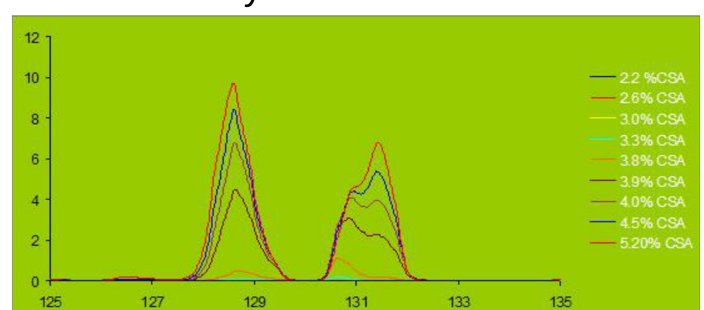
Dissimilarity Plot of Defect Region

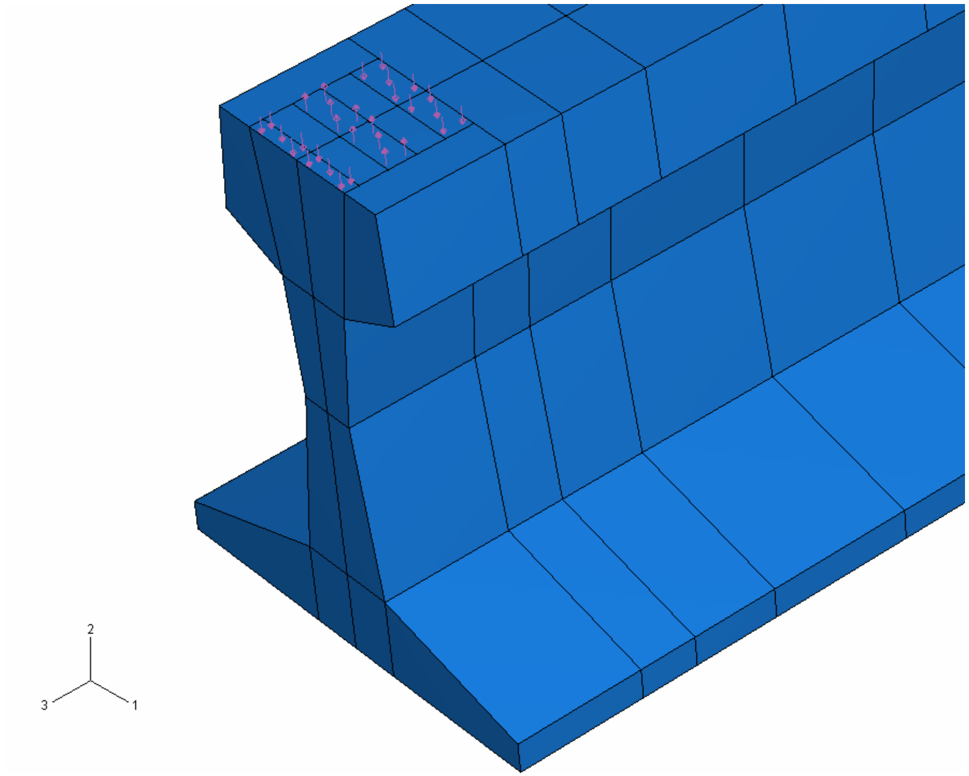


Max Plot of Back Wall Echo

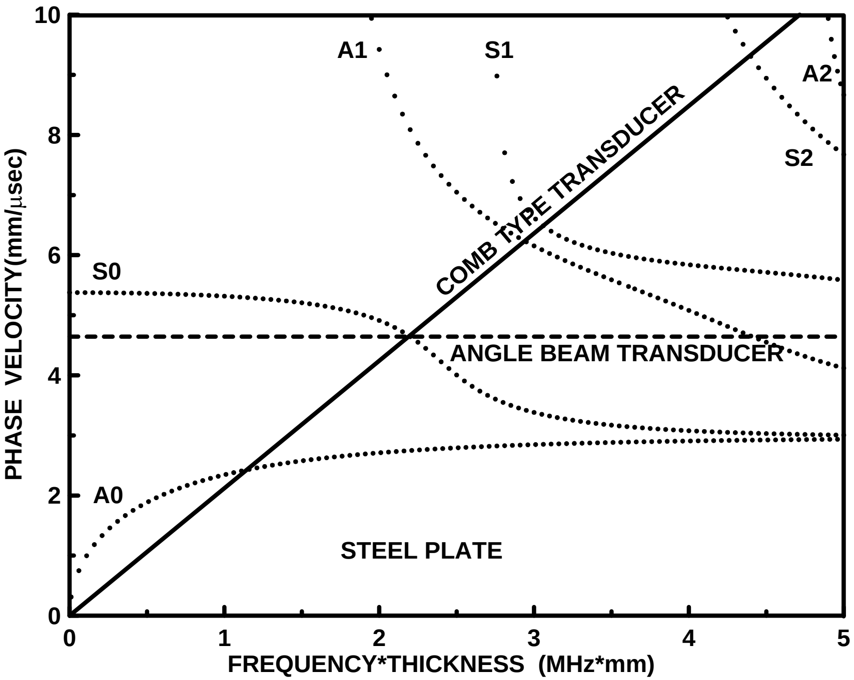


Dissimilarity Plot of Back Wall Echo



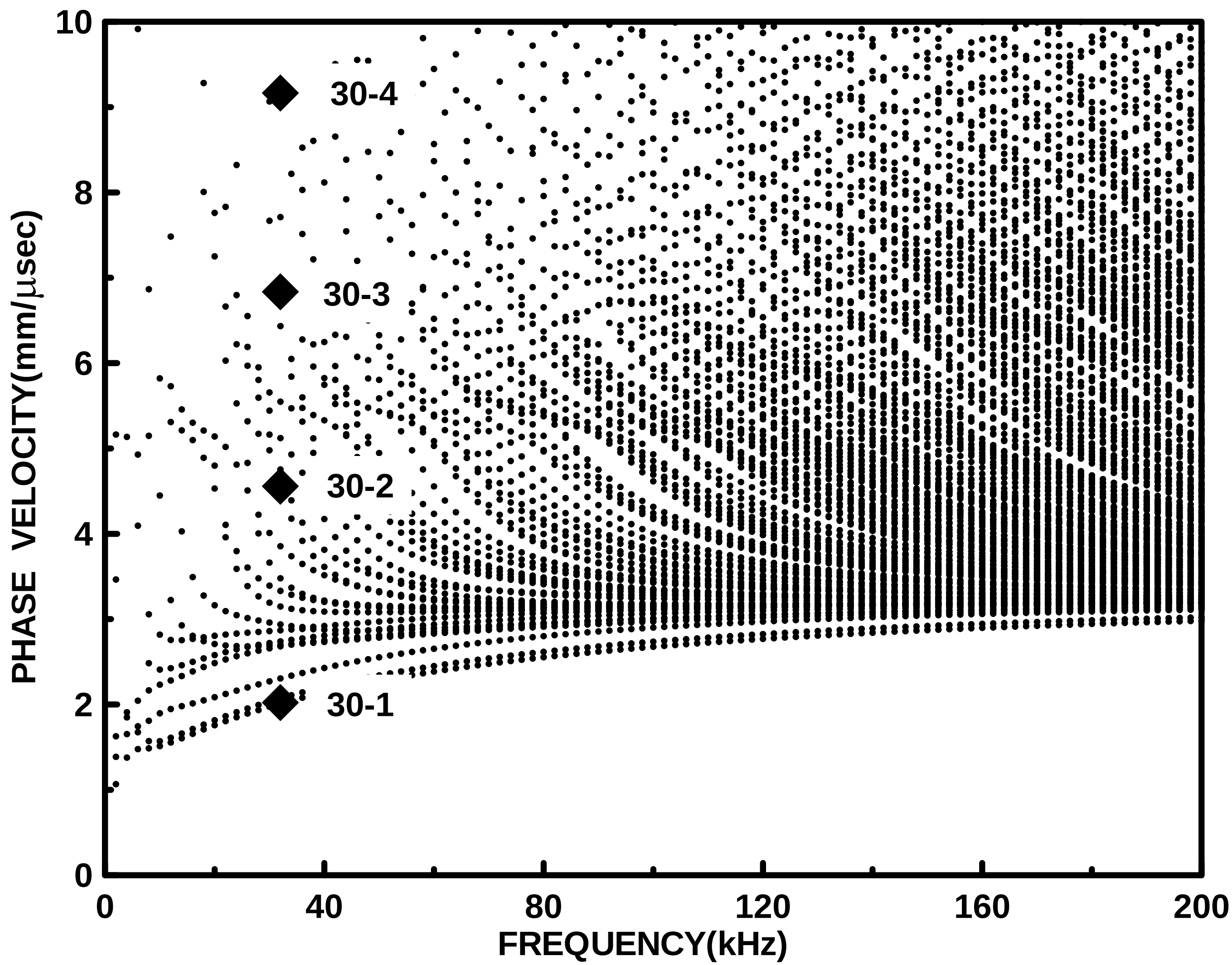


EMAT loading simulation



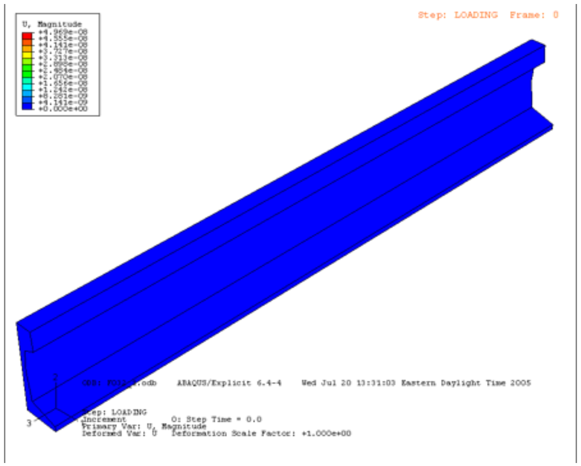
wave length : c_p / f

Slope : c_p / fd

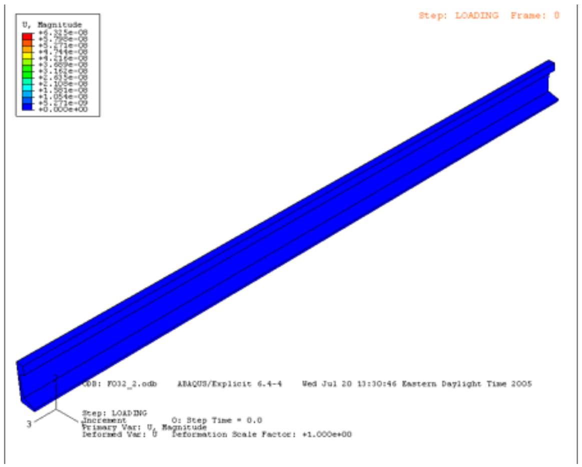


10
8
6
4
2
0
PHASE VELOCITY(mm/μsec)
30-4
30-3
30-2
30-1
0
40
80
120
160
200
FREQUENCY(kHz)

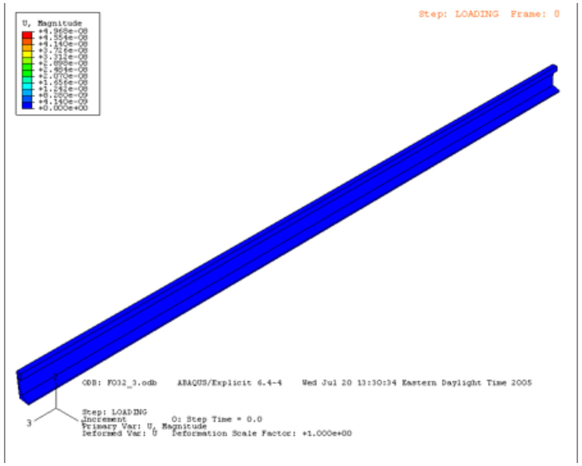
WAVE PROPAGATION AT 30kHz



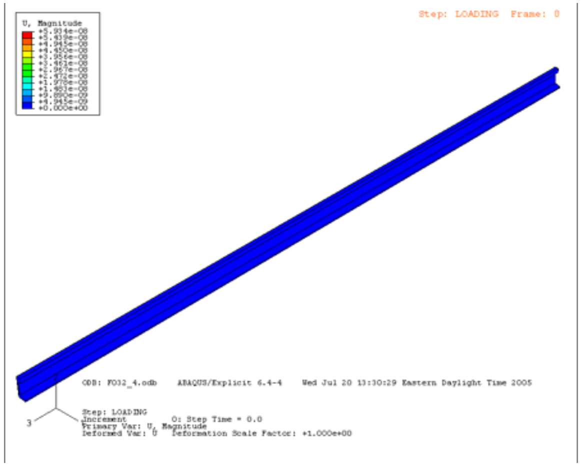
30-1



30-2



30-3



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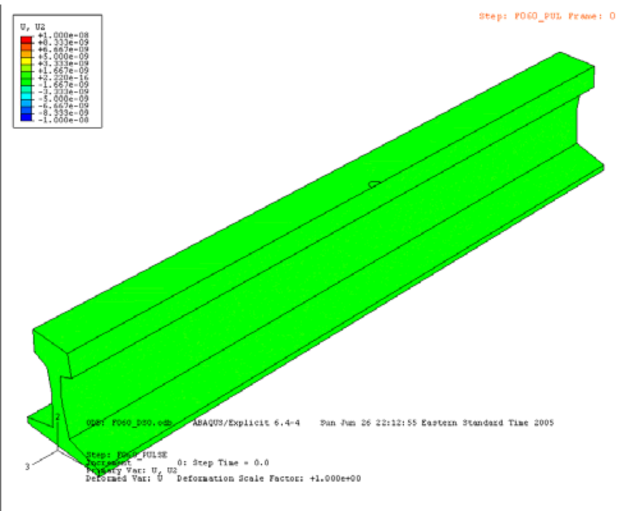
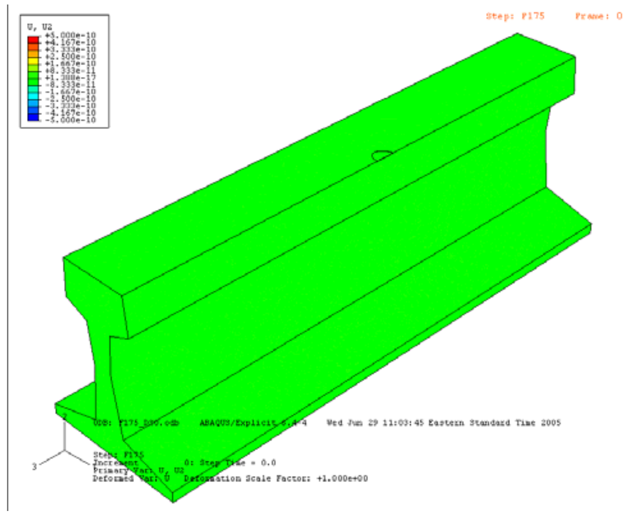
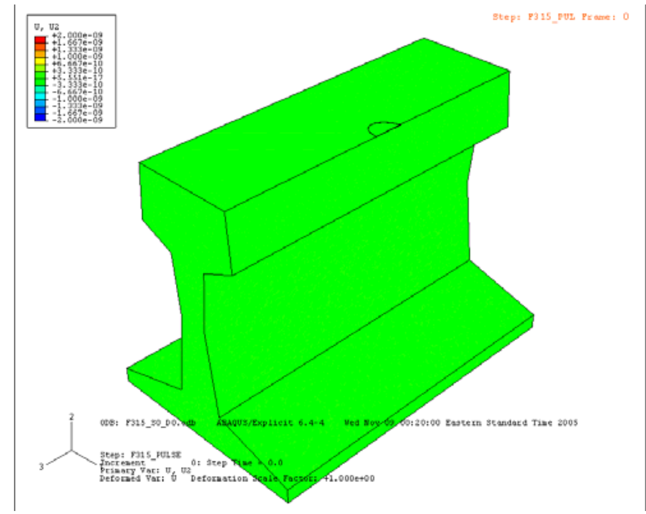


60kHz

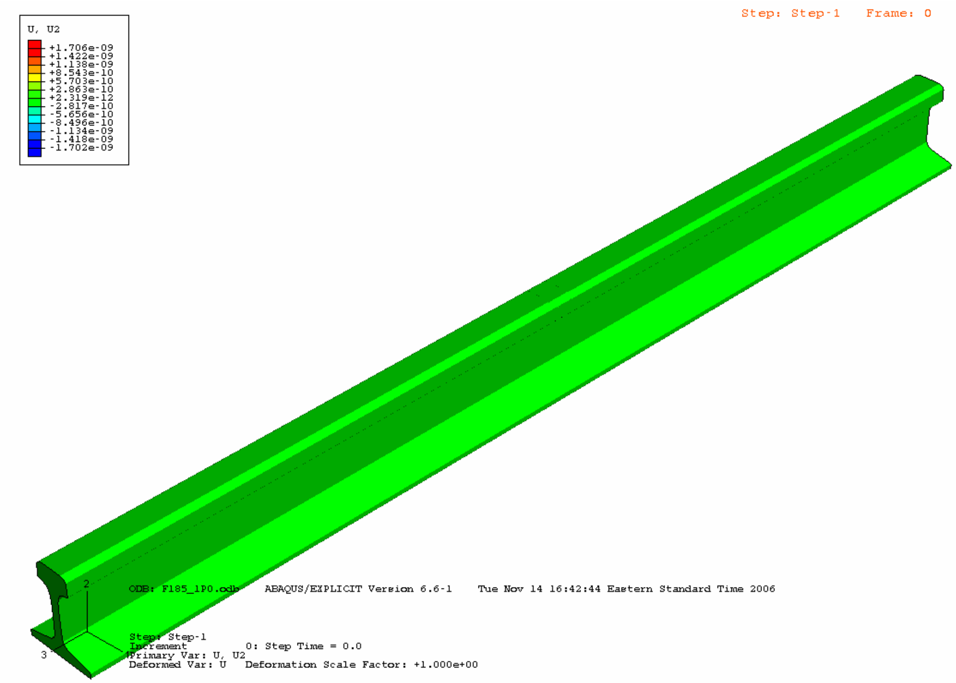


175kHz



315kHz

185kHz, Vertical Displacement



Conclusions

- Guided wave technology is now ready to adapt to new problems as they arise.
- NDE and SHM will explode in the future since total replacement of all infrastructure at one time is not possible.
- Wireless application on the horizon.