Ultrasonic Guided Waves for NDT and SHM

Joseph L. Rose
Paul Morrow Professor
Engineering Science & Mechanics Department
Penn State University

Chief Scientist
FBS, Inc.

CAV Presentation
May 4, 2009
<table>
<thead>
<tr>
<th>NDT</th>
<th>SHM</th>
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<tbody>
<tr>
<td>Off-line evaluation</td>
<td>On-line evaluation</td>
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<tr>
<td>Time base maintenance</td>
<td>Condition based maintenance</td>
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<tr>
<td>Find existing damage</td>
<td>Determine fitness-for-service and remaining useful time</td>
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<tr>
<td>More cost and labor</td>
<td>Less cost and labor</td>
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<tr>
<td>The testing system is independent from the test bed</td>
<td>The testing system is integrated into the test bed</td>
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<td><strong>Baseline not needed</strong></td>
<td><strong>Needs baseline.</strong></td>
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<td></td>
<td>Increase vehicle service time while maintaining safety standards</td>
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<td></td>
<td>More requirements for algorithm, energy harvest, data transportation and processing</td>
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A Comparison of the Currently Used Ultrasonic Bulk Wave Technique and the Ultrasonic Guided Wave Inspection Procedure

<table>
<thead>
<tr>
<th>Bulk Wave</th>
<th>Guided Wave</th>
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<tbody>
<tr>
<td>Tedious and time consuming</td>
<td>Fast</td>
</tr>
<tr>
<td>Point by point scan (accurate rectangular grid scan)</td>
<td>Global in nature (approximate line scan)</td>
</tr>
<tr>
<td>Unreliable (can miss points)</td>
<td>Reliable (volumetric coverage)</td>
</tr>
<tr>
<td>High level training required for inspection</td>
<td>Minimal training</td>
</tr>
<tr>
<td>Fixed distance from area of concern required</td>
<td>Any reasonable distance from defect acceptable</td>
</tr>
<tr>
<td>Defect must be accessible and area seen</td>
<td>Defect can be hidden</td>
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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
Typical wrap around ultrasonic guided wave sensor arrangement for long range ultrasonic guided wave inspection of piping
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, soil, insulations, 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.
The phase velocity dispersion curves of a 16 in. schedule 30 steel pipe:
(a) longitudinal groups,
(b) torsional groups.
Sample GROUP velocity dispersion curves in an elastic bare pipe

The group velocity dispersion curves of a 16 in. schedule 30 steel pipe:
(a) longitudinal groups,
(b) torsional groups.
All guided wave problems have associated with them the development of appropriate dispersion curves and corresponding wave structures. Of thousands of points on a dispersion curve, only certain ones lead to a successful inspection i.e.: displacement on the outer, center, or inner surface, with only in-plane vibration on the surface to avoid leakage into a fluid, with minimum power at an interface between a pipe and a coating, etc.
“Phase velocity spectrum”

Non-dispersive for L [0, 1] and T [0, 1] families

Spectra of a 0.5 MHz Hanning tone burst (typical piezoelectric excitation)

“source,” is a piezoelectrically generated, 500 kHz pulse.
Non dispersive
Dispersive
Why Study Flexural Modes?

1. For possible natural focusing in pipe.
2. For possible phased array focusing in pipe.
3. To understand reflection from defects that are generally flexural in nature.
4. Can use with limited circumferential access to a pipe.
5. Can use to inspect elbows and beyond.
Boiler Tubing Guided Wave Inspection Potential

Less than 180 circumferential loading
Figure 2(a). Circumferential displacement distribution at $z = 4 \text{ m}, f = 0.25 \text{ MHz}$ (maximum point)

Figure 2(b). Circumferential displacement distribution at $z = 4 \text{ m}, f = 0.35 \text{ MHz}$ (minimum point)
Sample Inspection Output with High Frequency System (4” schedule 40 steel Pipe)

Defect 1: .36% Cross Sectional Area (CSA) internal simulated corrosion, 24” from end

Defect 2: .64% CSA external simulated corrosion, 48” from end

Defect 3: 1.18% CSA external simulated corrosion, 120” from end
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
Axisymmetric guided wave inspection concept
Guided wave focal scan concept
# Principal benefits of phased-array focusing for pipe inspection

<table>
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<tr>
<th>Benefit</th>
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<tr>
<td>Improved defect probability of detection (less than 3% CSA for focusing, compared to more than 5% CSA for axisymmetric)</td>
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<tr>
<td>Decreased defect false alarm rate</td>
</tr>
<tr>
<td>Increased inspection confidence</td>
</tr>
<tr>
<td>Excellent defect circumferential location analysis</td>
</tr>
<tr>
<td>Improved signal to noise ratio compared to axisymmetric</td>
</tr>
<tr>
<td>Six to infinite $dB$ defect signal improvement compared to axisymmetric</td>
</tr>
<tr>
<td>Increased penetration power in a coated pipeline with high attenuations</td>
</tr>
<tr>
<td>Potential characterization and defect sizing</td>
</tr>
<tr>
<td>Ability to determine circumferential profile of value in reflector characterization</td>
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Experimental Setup

TeleTest® tool mounted on a pipe, 44 modules, 4 channels shown.
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
Guided Wave Detection Sensitivity Concept Curves (Bare and Coated Pipe)
Disbond Detection with Circumferential Guided Waves

Coating disbond regions serve as initiation points for corrosion. FBS has identified several guided-wave features that provide a coating disbond "signature". These include:

- Increased Time-of-Flight as compared to a fully coated pipe (see illustration)
- Increased attenuation (see illustration)
- High-frequency filtering effect

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<tr>
<th>Disbond Size</th>
<th>TOF (µs)</th>
<th>Velocity (mm/µs)</th>
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<tbody>
<tr>
<td>0&quot; (not shown)</td>
<td>623.9</td>
<td>3.07</td>
</tr>
<tr>
<td>11&quot;</td>
<td>617.5</td>
<td>3.10</td>
</tr>
<tr>
<td>32&quot;</td>
<td>606.3</td>
<td>3.16</td>
</tr>
<tr>
<td>75&quot; (bare)</td>
<td>591.9</td>
<td>3.24</td>
</tr>
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</table>
Tomographic Methods in Pipe and Composite Inspection
Guided wave computed tomography (CT) concept and embedded array possibilities
Tomography

- Ultrasonic transducers placed in an array around an area of interest

- Damage Location suggested by the intersection of affected paths

Reconstruction Algorithm for Probabilistic Inspection of Damage (RAPID)

\[ P(x,y) = \sum_{k=1}^{N} \frac{A(x,y)}{\beta - 1} R(x, y, x_{1k}, y_{1k}, x_{2k}, y_{2k}) + \frac{\beta}{\beta - 1} \]

Signal difference coefficient (SDC)

\[ SDC = 1 - \rho \]

\( \rho \) - correlation between signals in the reference and damaged states

\( R \) - ratio of distance of the path taken and line of sight
Critical Section Monitoring

Tomographic pipeline SHM (one defect only induced and growing at DS-1, DS-2 and DS-3 time periods, a second defect added at time periods DS-4, DS-5 and DS-6 time periods)
Pipe Description:
4” Schedule 40 Steel Pipe

Damage Size:
0.5” diameter
0.009” (3.6%) wall loss

Figure 11. Tomographic pipe elbow SHM showing interior erosion simulation via acid etch.
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

Sensor network on the wing
Comparison

Before Corrosion Simulation

After Corrosion Simulation
Guided wave air coupled scanning system
Attenuation dispersion curve in the quasi-isotropic composite laminate
Lamb Wave in Anisotropic Plate

- Skew angle for the second symmetric mode at $f_d = 1.05$ MHz-mm
Skew angle dispersion curves

\[ tg(\Phi) = \frac{\int_{H}^{H} P_{x_2} \, dx_3}{\int_{H}^{H} P_{x_1} \, dx_3} \]

Continuous lines: SAFE;
Blue dots: Global matrix method.
Wave propagation in 0° direction.
Annular Array Sensor Design for Improved Guided Wave Structural Tomography
Let’s consider a sample problem of flaw detection on a water loaded plate
What could be done to produce a better result? To avoid a false alarm?

Aha, maybe a better sensor design!

But first what mode and frequency do I want to generate?
Sensor Design for Inspection

Sensor 1

Sensor 2
Corroding an Aluminum plate

Corroding an aluminum plate using salt water and accelerating with a battery
Corrosion detection with Sensor 1

13% corrosion defect

Dry Aluminum Plate with a 13% corrosion defect

Tomogram obtained with A0 mode at 350 KHz

Tomogram after false-color filtering

Wet Aluminum Plate with a 13% corrosion defect

13% corrosion defect

Water Traces

Tomogram obtained with A0 mode at 350 KHz
Corrosion detection with Sensor 2

6% corrosion defect

Dry Aluminum Plate with a 6% corrosion defect

Tomogram obtained with S1 mode at 2.4 MHz

Tomogram after false-color filtering

Corrosion

6% corrosion defect

Wet Aluminum Plate with a 6% corrosion defect

Water traces

Tomogram obtained with S1 mode at 2.4 MHz
Gas entrapment determination with Ultrasonic Guided Waves

Volume = 1,268 in$^3$

Pipe specimen profile.

Energy feature value

% Air volume

y = 0.004x - 0.211
$R^2 = 0.9739$

170 kHz excitation

Air volume (in$^3$)
De-icing/Anti-icing with Guided Waves

**Product Description:** Guided wave energy is utilized to create maximum shear stresses at the ice/airfoil interface, causing instantaneous delamination.

**Competition:** Electrothermal, Mechanical boot

**Advantage:** Instantaneous delamination, requires less energy, Ultrasound does not harm the structure as heat can, Can also be used to remove mud or other materials

**Product Availability:** Under Development
Ultrasonic Guided Wave De-Icing Using a Multi-Actuator Mode Tuning Focusing Approach

January 29th, 2008

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Mud Removal with Guided Waves

Ultrasonic De-Mudding System
Proof-of-Concept Experiment

April 2008

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Concluding Remarks

• Advances in guided wave understanding and computational power are making guided wave inspections a reality today.

• Of particular significance are applications in aircraft, pipelines, and bridges.

• New directions point to NDE and SHM with inexpensive sensor and sparse arrays for line of sight analysis, phased array work, and ultrasonic guided wave tomographic imaging.

• Besides defect detection and location analysis for screening, new work also points to more detailed quantitative characterization analysis.