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Determining the Optimal Parameters in a Distant Radar NDE Technique for Debonding Detection of GFRP-Concrete Systems

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Outline

- Introduction
- Motivation and scope of research
- Theory – Far-field airborne radar NDT
  - Distant ISAR (inverse synthetic aperture radar) measurement
  - Backprojection algorithms
  - Morphological processing
- Application
  - GFRP-concrete cylinder
- Summary and Discussion
- Acknowledgements

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Introduction

- Problem – Sudden failures of civil infrastructure systems
  - Significant impacts
  - Catastrophic results
- Approaches to the problem –
  - Condition assessment of structures
  - Strengthening and repair of structures
- In both approaches, assessment techniques are the pivotal capability in the success of these approaches.
- **Fact**: The U.S. infrastructure receives an overall grade of D, indicating that America has a infrastructure that is poorly maintained, unable to meet current and future demands, and in some cases, unsafe and suggesting a total cost of $2.2 trillion for repair.

(Source: ASCE 2009 Report Card for America's Infrastructure)

Introduction (cont’d)

- Sudden failures of civil infrastructure systems
  - Significant impacts
    - EX: I-35 Highway Bridge Collapse, Minneapolis, Minnesota (6:05pm, Wed., Aug. 1, 2007)

(Source: Security camera by the Army Corps of Engineers)

(Source: www.gettyimages.com)

→ We don’t want to see this happen again. But, do we have a solution?

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Introduction (cont' d)

- Sudden failures of civil infrastructure systems
  - Catastrophic results – I-35 Highway Bridge Collapse, MN
    - Causality: 13 deaths, 98 victims (Mn/DOT, Aug. 3, '07)
    - Cost of emergency response: $8 million from Mn/DOT, $250 million from the Congress
    - Business activities: $1.5 million to local small businesses (U.S. Small Business Administration, Aug. 24,' 07)
    - Road-user cost due to detouring: $400k/day (Mn/DOT, Office of Investment Management, Aug. 6, '07)
    - Rebuild cost: $234 million (project awarded to the Flatiron-Manson and FIGG Bridge Engineers by Mn/DOT, Oct. 8, '07)
    - Other associated costs and expenses for the rehabilitation (??)

→ Original cost of the bridge: $5.27 million (value in 1964)

[$32.11 million (current value of original cost)

<< more than $493.5 million (rehabilitation and rebuild cost)]

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Introduction (cont' d)

- Condition assessment of structures
  - In addition to the I-35W bridge, there are approximately 75,000 other U.S. bridges also rated as "structurally deficient" in 2007.
    - Structurally deficient: The structure is deemed to have met minimum tolerable limits to be left in place as it is.

→ Are these 75,000 structurally deficient bridges safe? How do we know for sure?

→ We need <u>reliable</u> (inspection results are creditable), <u>efficient</u> (inspection can be accomplished in time) condition assessment technologies for this challenging problem.

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Introduction (cont' d)

- Strengthening and repair of structures
  - For intact structures: To upgrade their design capacity
  - For damaged structures: To restore their design capacity
  - Novel composite materials (fiber reinforced polymer, FRP) have been widely used, such as glass FRP, carbon FRP, & aramid FRP.

→ How is an appropriate level of strengthening determined?

→ We need condition assessment technologies for (1) determining the level of strengthening and (2) evaluating the quality of strengthening.

(Source: Fyfe Co. LLC, 2005)

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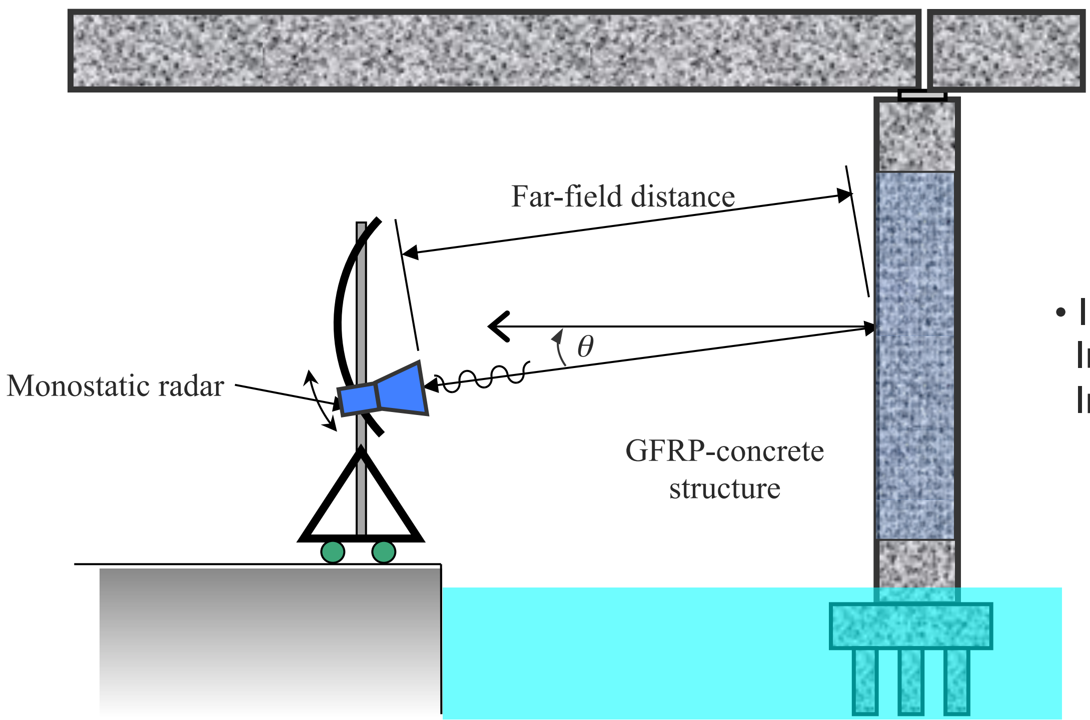
Introduction (cont' d)

- A far-field airborne radar (FAR) NDT technique* is proposed for the distant, in-depth assessment of concrete structures.



- Inspection parameters: Incident frequency and Incident angle

[* Yu, T.-Y., and O. Buyukozturk, *NDT&E Intl*, 4:10-24, 2008.]

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Motivation and Scope

- Determining the optimal range of incident frequency and incident angle for defect detection is crucial in field applications. → For efficient inspection
- Questions must be answered:
  1. There are different types of defects in real situations. How do we model them?
  2. What is the objective function in determining the optimal range of incident frequency and angle?

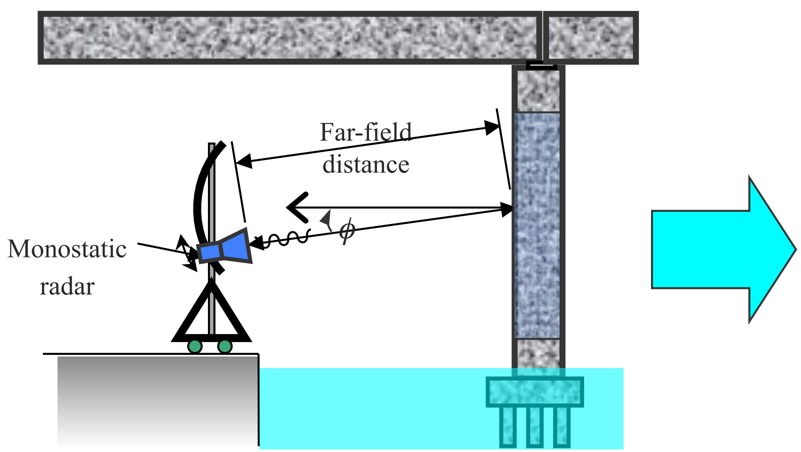
→ Start with simplified artificial defects to understand the pattern of defects.

→ Need to quantify the detectability in the FAR NDT technique for optimization.

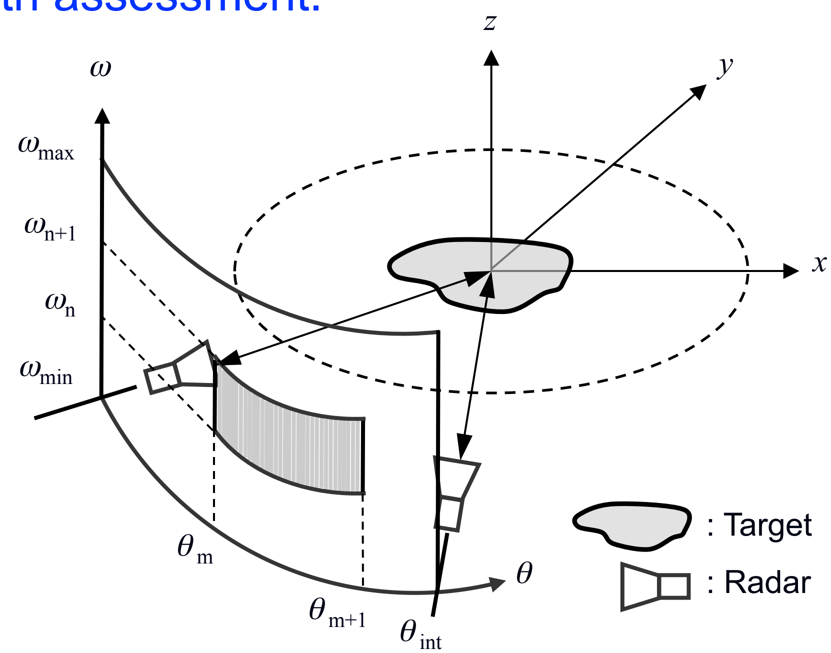
Theory

- Components in the FAR NDT technique:
  - Distant inspection – Reflection measurements made in a range beyond the far-field distance.→ Distant ISAR (inverse synthetic aperture radar) measurements
  - Data processing – Backprojection processing of ISAR measurements and morphological processing of backprojection images

→ Distant inspection provides in-depth assessment.



Field configuration of FAR NDT



Concept of data plane

Theory (cont'd)

- Distant ISAR measurement –
  - Time-dependent scattering response of a point scatterer:

$$S(\bar{r}_{s,j}, t) = \frac{1}{R_{s,j}^2} \int_{\omega_c - \pi B}^{\omega_c + \pi B} d\omega \cdot \exp[i\omega t] \qquad (1)$$

  - Range-compressed scattering response:

$$S(\bar{r}_{s,j}, \hat{t}) = \frac{B}{R_{s,j}^2} \exp[i\omega\hat{t}] \cdot \mathrm{sinc}(B\hat{t}) \qquad (2)$$

  - Integrated ISAR response:

$$D(\xi, \hat{t}) = \int_0^{R_s} d\bar{r}_j \int_0^{2\pi} d\phi_j \cdot G(\bar{r}_j, \phi_j) S(\bar{r}_{s,j}, \hat{t}) \qquad (3)$$

Theory (cont'd)

- Backprojection algorithms* –
  - Backprojection image:

$$I(\bar{r}, \phi) = \int_0^{R_s\theta_{\text{int}}} d\xi \cdot F(\xi, \hat{t}) \quad (4)$$

  - Image reconstruction:
    - Bandpass transformation (C_{bp} is the backprojection coefficient to yield an ideal bandpass function)

$$F(\xi, \hat{t}) = C_{bp} \cdot \frac{\partial D(\xi, \hat{t})}{\partial t}$$

    - Matched filtering

$$\frac{\partial D(\xi, \hat{t})}{\partial t} = \frac{\partial}{\partial t} \int_0^{\hat{t}} dt' \cdot D(\xi, \hat{t}) \cdot M(\hat{t} - t') = \int_0^{\hat{t}} dt' \cdot D(\xi, \hat{t}) \cdot \frac{\partial M(\hat{t} - t')}{\partial t}$$

[* Yu, T.-Y., and O. Buyukozturk, *Proc. SPIE 6934*, San Diego, CA, 2008.]

Theory (cont'd)

- Morphological processing – To extract and quantify the reconstructed backprojection images
  - Feature extraction:
    - Erosion operator

$$\epsilon_K(I) = \{\bar{r} | K_r \subset I(x,y)\} \quad (5)$$

    - Dilation operator

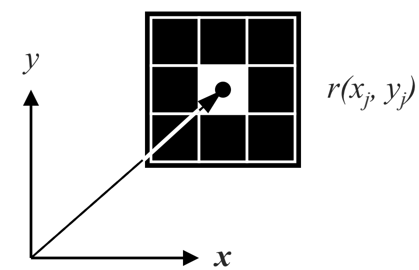
$$\delta_V(I) = \{\bar{r} | V_r \cap I(x,y) \neq \emptyset\} \quad (6)$$

  - Feature-extracted images:

$$\hat{I}(x,y|n_{thv}) = \delta_V\left[\epsilon_K\left[I_{BW}(x,y|n_{thv})\right]\right] \quad (7)$$

  - Quantification index: Euler's number

$$n_E(\theta|n_{thv}) = n_{obj}(\theta|n_{thv}) - n_{hol}(\theta|n_{thv}) \quad (8)$$



An eight-node morphological structure

Theory (cont’d)

- Morphological processing *(cont’d)* –
  - Low-pass filtering (for global assessment purpose):

$$n_E^f(\theta) = \sum_{\theta=-\theta_{int}/2}^{\theta_{int}/2} \frac{n_E(\theta)}{L} \qquad (9)$$

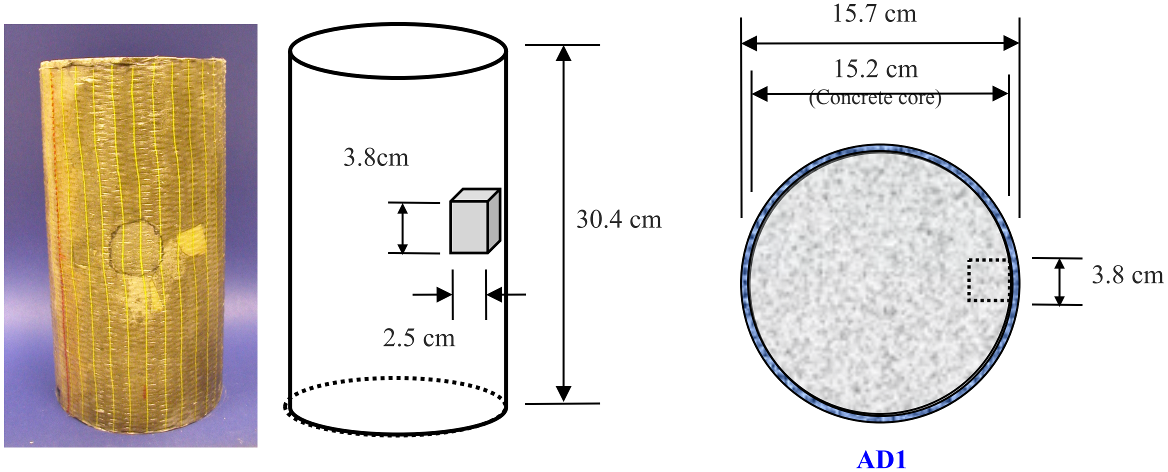
where L is the length of the low-pass filter.

- Optimization – To yield maximum differential Euler’s number

$$\Omega_{opt} = \max_{n_E \in Z} \left[\Delta n_E \left(B_{opt}, \theta_{opt}\right)\right] \qquad (10)$$

Application

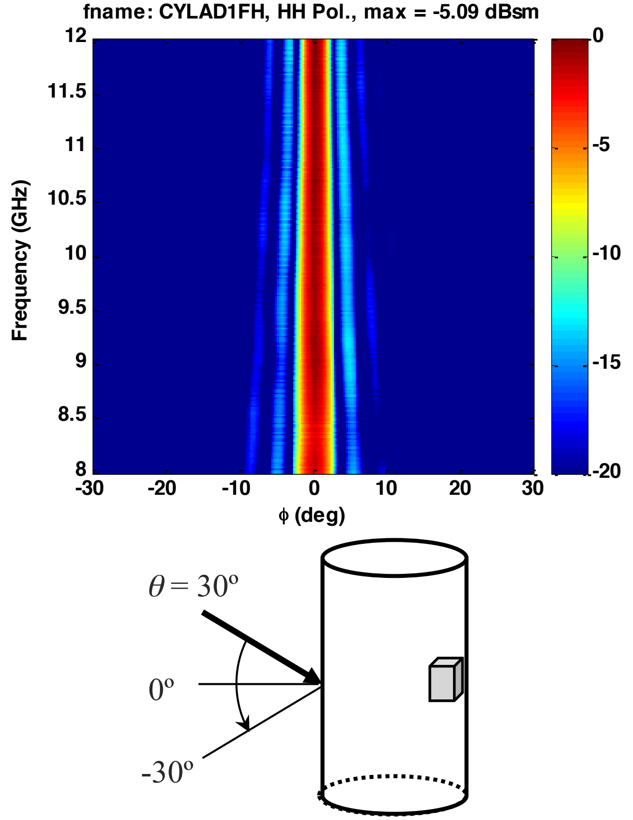
- GFRP (glass fiber reinforced polymer)-wrapped concrete cylinder specimens with an artificial defect:



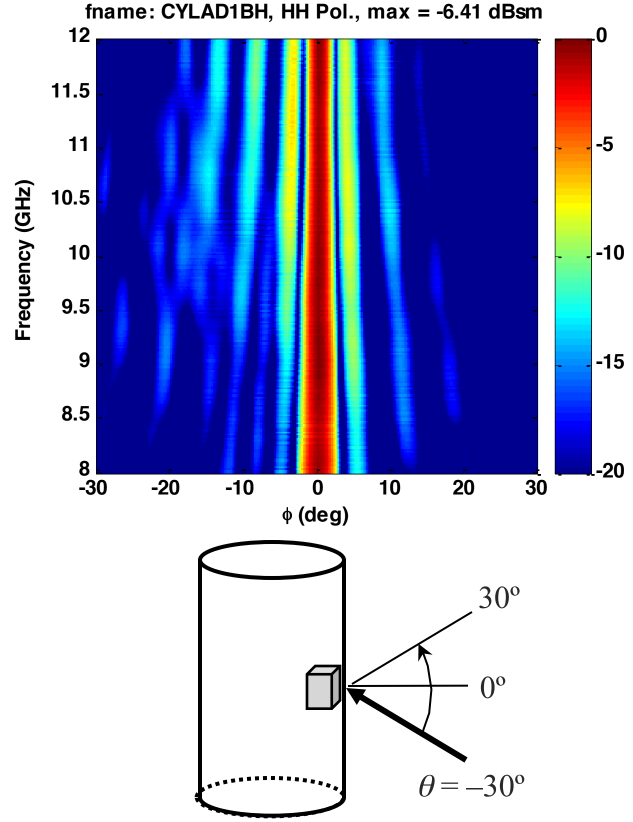
- Concrete mix ratio (by weight) = water:cement:sand:aggregate = 0.45:1:2.52:3.21
- GFRP mix ratio (by volume) = epoxy:glass fiber = 0.645:0.355
- GFRP type = Tyfo SHE-51A by Fyfe / Epoxy = Tyfo S epoxy by Fyfe.
- GFRP sheet thickness = 0.25 cm. (0.1 in.)

Application (cont' d)

- Distant ISAR measurements:
  - HH-polarized signals in X-band (8GHz~12GHz), θ = -30º~30º, oblique incident scheme



(a) Specimen
– Intact side



(b) Specimen
– Damaged side

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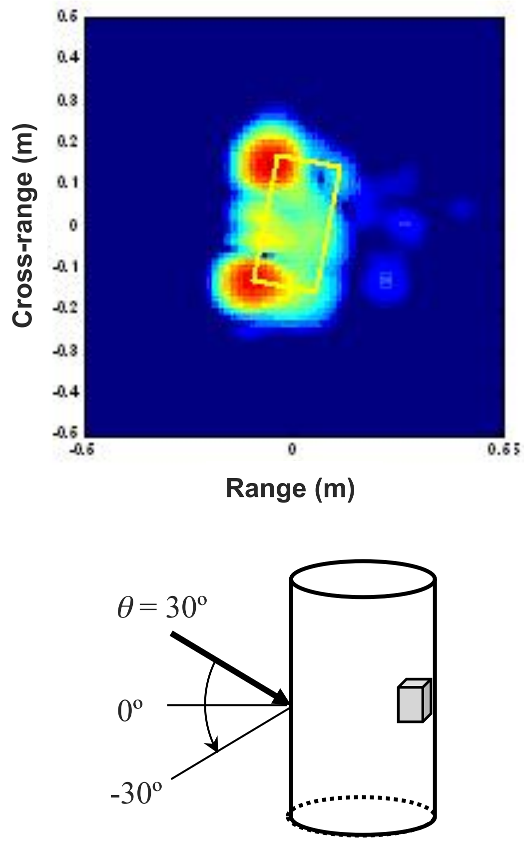
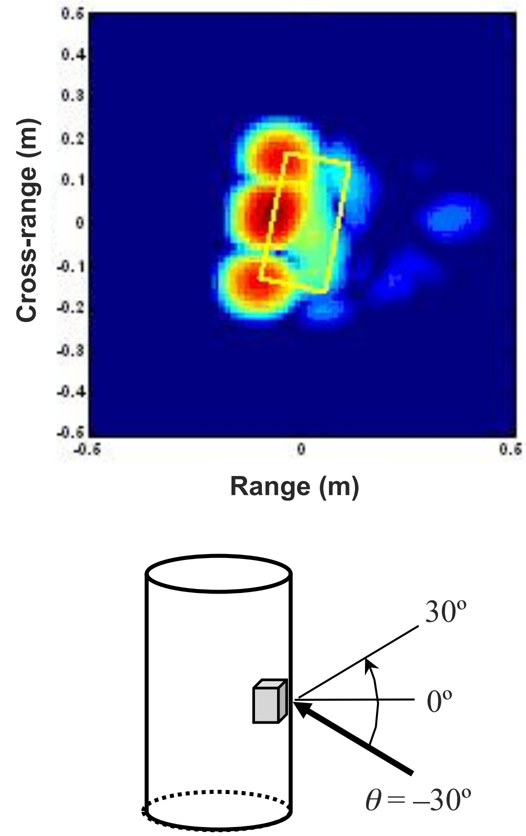
Application (cont' d)

- Reconstructed backprojection images: θ = -10º



(a) Specimen AD1
– Intact side

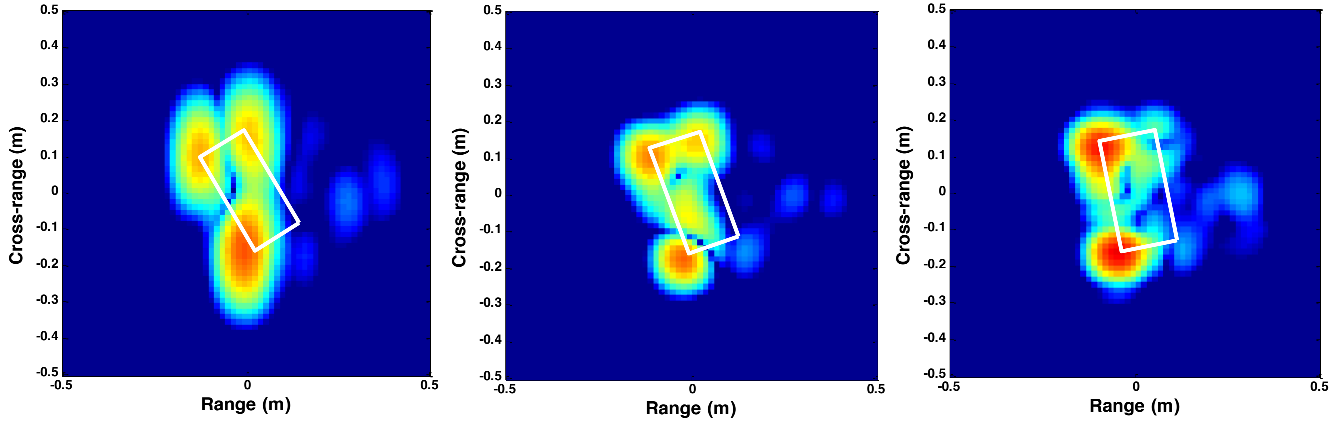


(b) Specimen AD1
– Damaged side

[* Yu, T.-Y., and O. Buyukozturk, *Proc. SPIE 6934*, San Diego, CA, 2008.]

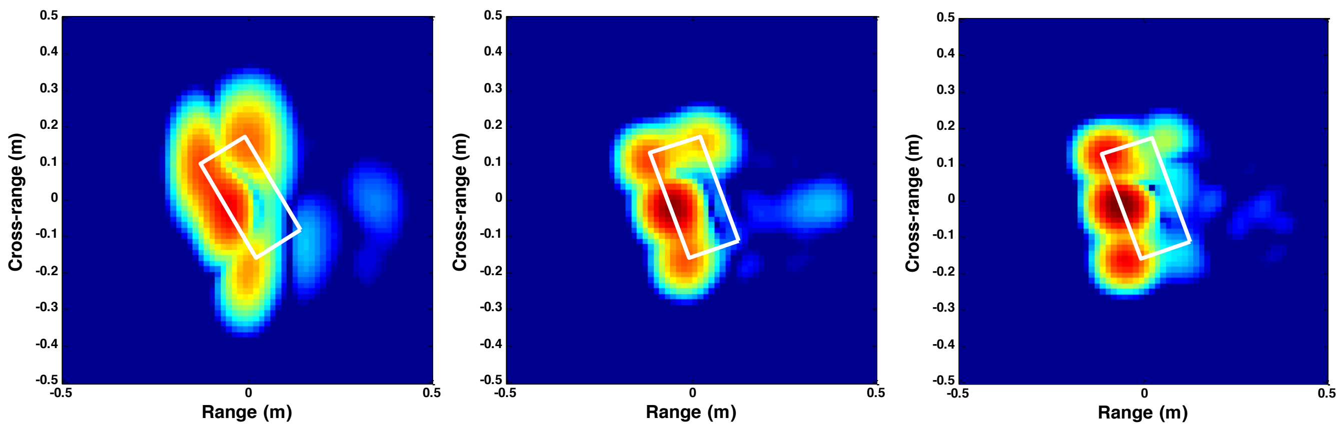
Application (cont' d)

- Effects of incident angle in reconstructed images –



(a-1) 30º (a-2) 20º (a-3) 10º

(a) Intact side

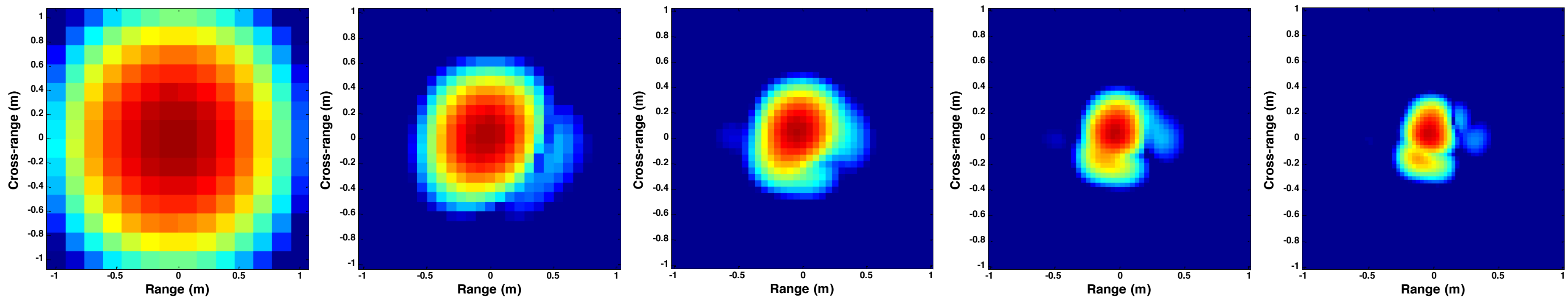


(b-1) 30º (b-2) 20º (b-3) 10º

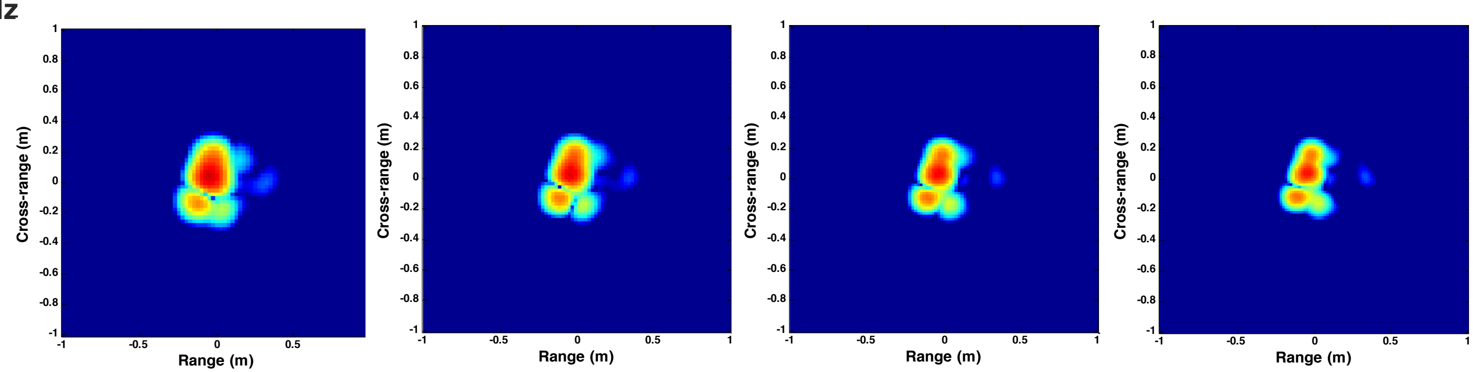
(b) Damaged side

Application (cont' d)

- Effects of bandwidth in reconstructed images –



(a) f_c = 8.2GHz, B = 0.4 GHz (b) f_c = 8.4GHz, B = 0.8GHz (c) f_c = 8.6GHz, B = 1.2GHz (d) f_c = 8.8GHz, B = 1.6GHz (e) f_c = 9.0GHz, B = 2.0GHz



(f) f_c = 9.2GHz, B = 2.4GHz (g) f_c = 9.4GHz, B = 2.8GHz (h) f_c = 9.6GHz, B = 3.2GHz (i) f_c = 9.8GHz, B = 3.6GHz

→ Increase used bandwidth = improve image resolutions (range and cross-range)

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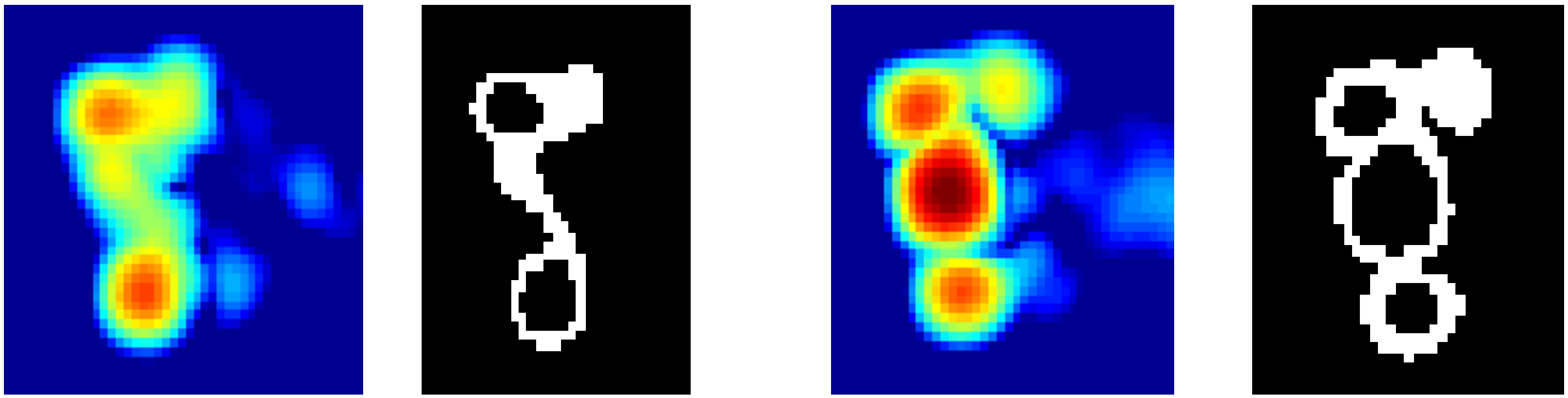
Application (cont’d)

- Feature-extracted backprojection images



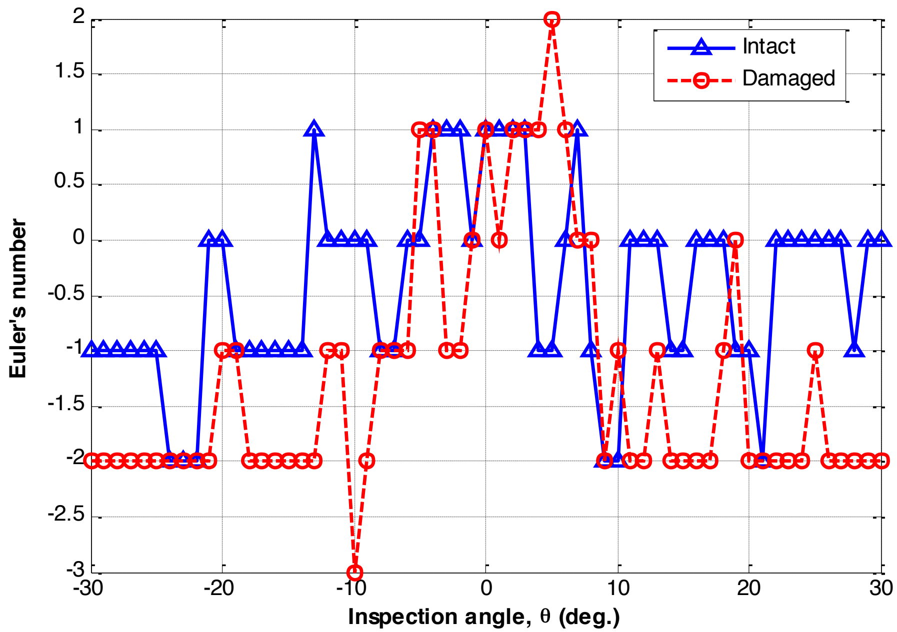
(a) Intact side images – n_{thv} = 0.81 (b) Damaged side images – n_{thv} = 0.73

→ Intact side: n_E = -1 → Damaged side: n_E = -2

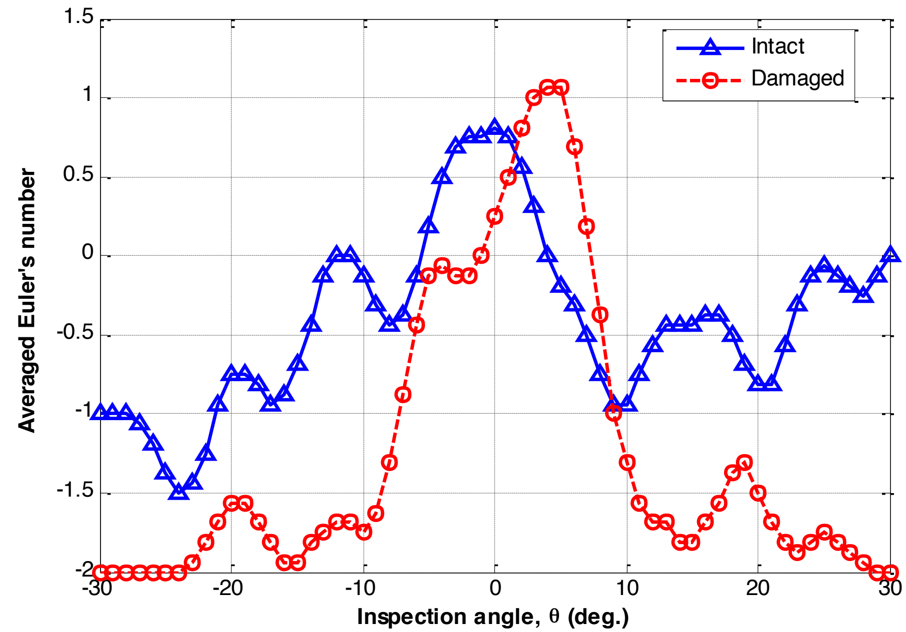
→The more different the Euler’s numbers for intact and for damaged sides, the better the detectability.

Application (cont’ d)

- Raw n_E curves and filtered n_E curves –



Raw n_E curves



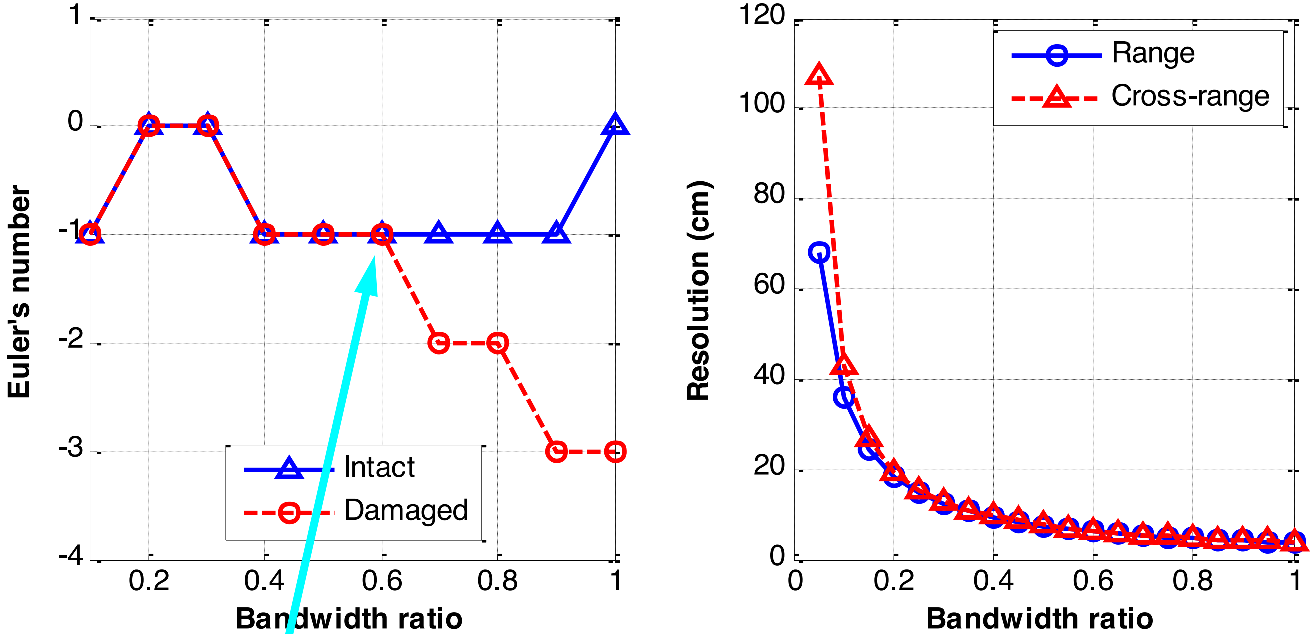
Filtered n_E curves (filter length = 3)

→We can use the minimum length of the low-pass filter as a basis for minimum amount of measurements to achieve consistent assessment.

→Optimal angle (or angular range) can be quantitatively determined by the maximum differential n_E.

Application (cont’d)

- Optimal bandwidth



(a) Bandwidth ratio vs. Euler’s number (b) Bandwidth ratio vs. resolutions

→Optimal bandwidth can be determined by the minimum needed bandwidth to achieve non-zero differential Euler’s numbers.

Summary and Discussion

- A methodology for quantitatively evaluating the backprojection images in FAR NDT is proposed.
- It is found that the use of a morphological index, Euler's number, can provide a basis for determining the optimal parameters (incident frequency (or bandwidth) and angle (or angular range)).
- The use of a low-pass filter is to achieve a globally consistent assessment. → This averaging step could reduce the contribution from some effective incident angles.
- The change of defect geometry will lead to the change of scattering pattern. → Need to perform a systematic investigation to consider different defects/damages.

Acknowledgements

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