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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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SERG

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
- Acknowledgement
- References

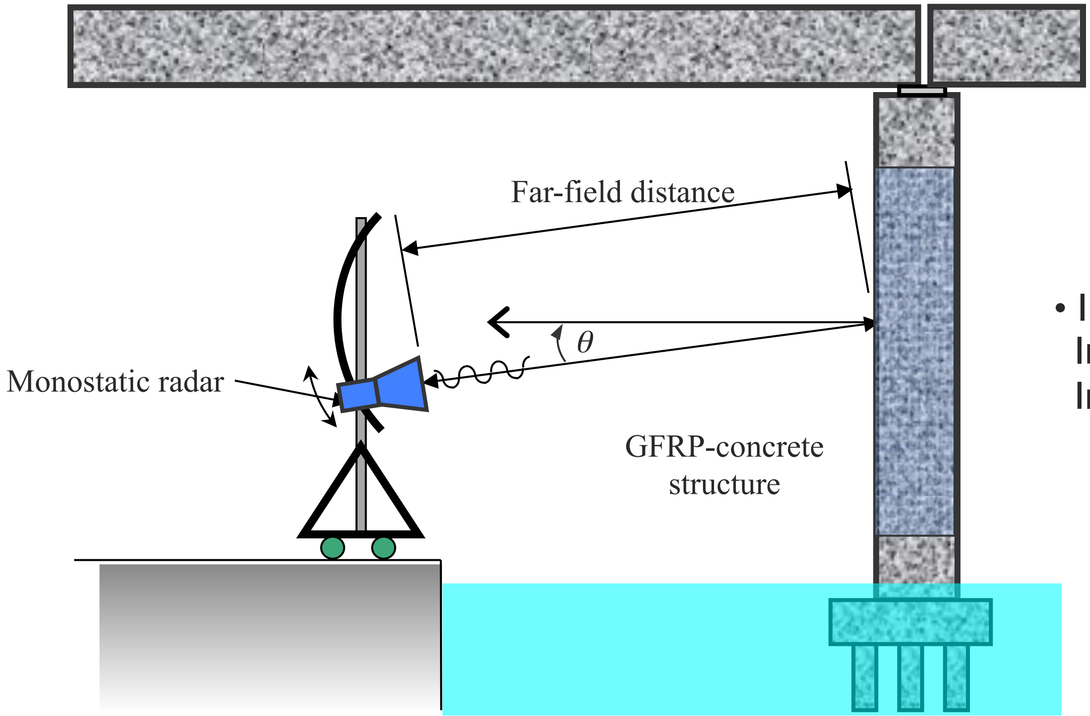
Introduction

- 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

- 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.]

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?

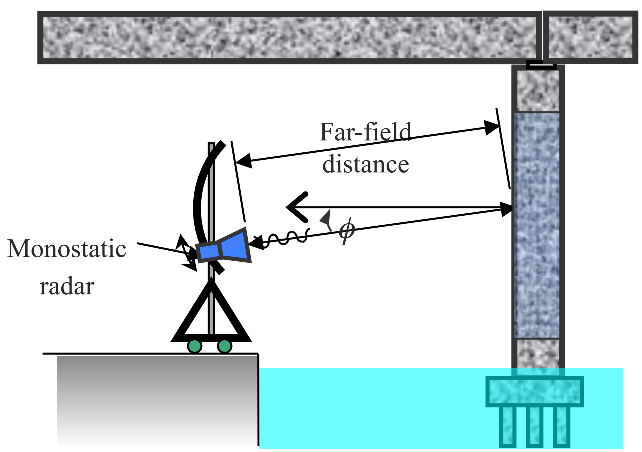
→ *Start with simplified artificial defects to understand the pattern of defects.*

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

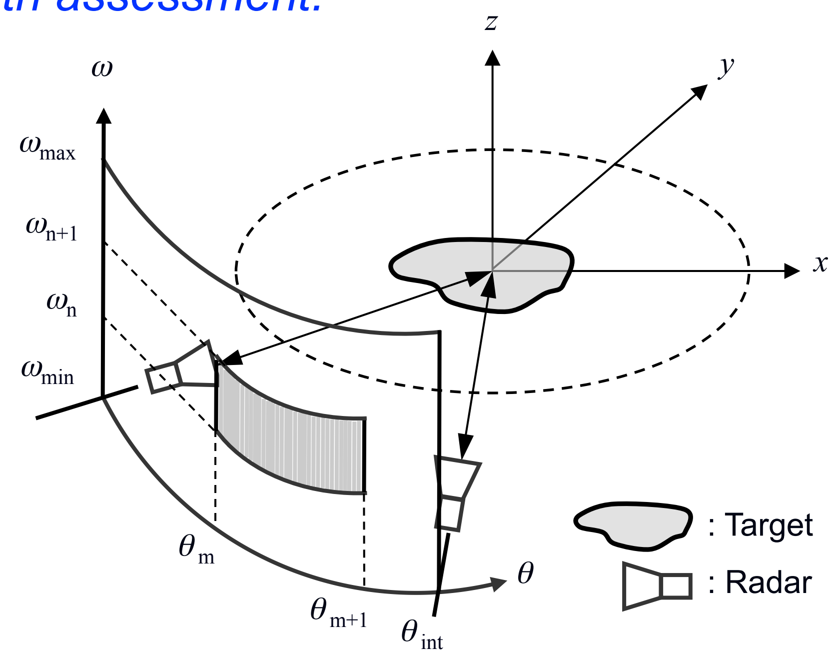
Theory

- 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

- 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

- Backprojection algorithms* –
  - Backprojection image:

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

  - 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

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

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

    - Dilation operator

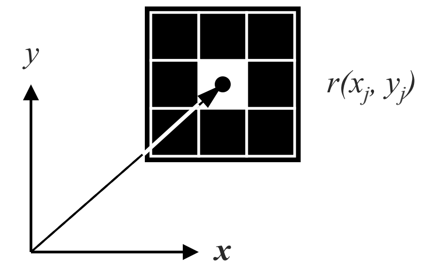
$$\delta_V(I) = \{\bar{r} | V_r \cap I(x,y) \neq \emptyset\} \tag{6}$$

  - Feature-extracted images:

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

  - Quantification index: Euler' s number

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



An eight-node morphological structure

Theory

- Morphological processing –
  - Low-pass filtering (for global assessment purpose):

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

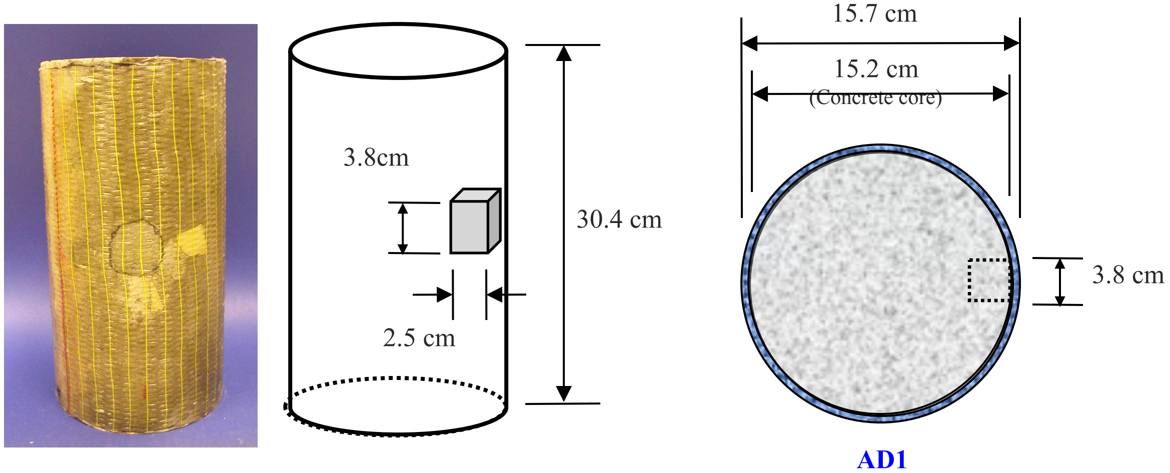
where L is the length of the low-pass filter.

- 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

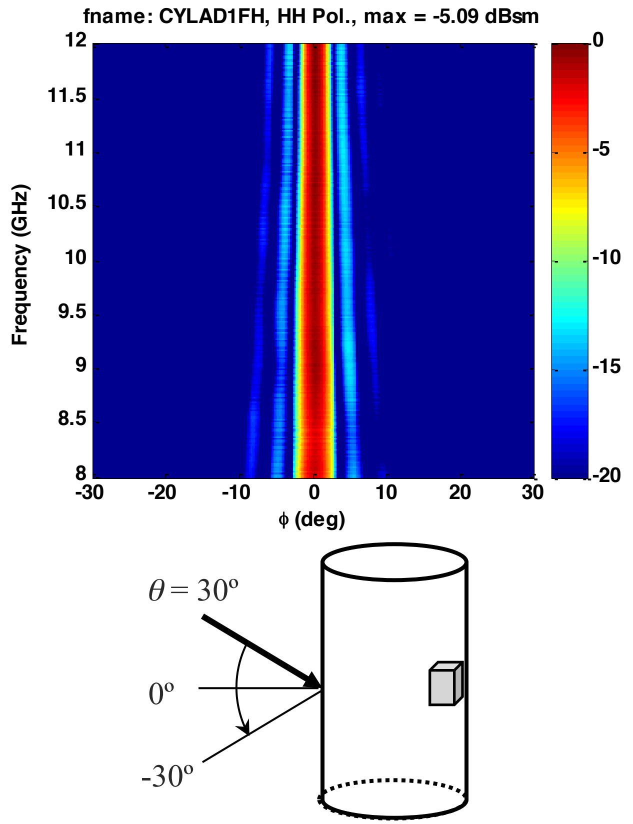
- GFRP (glass fiber reinforced polymer)-wrapped concrete cylinder specimens with an artificial defect:



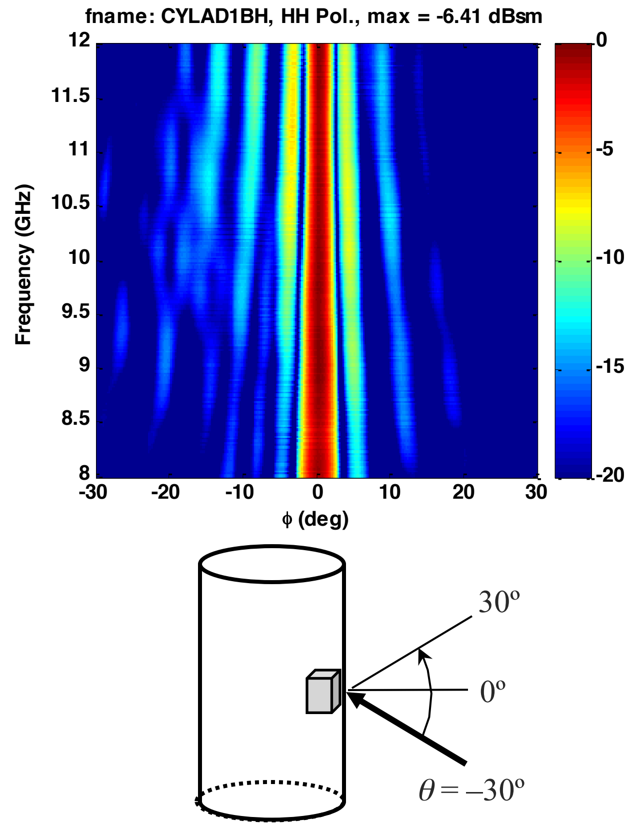
- Concrete mix ratio (by weight) = water:cement:sand:aggregate = 0.45:1:2.52:3.21
- GFRP mix ratio (by volume) = epoxy:glass fiber = 0.645:0.355
- GFRP type = Tyfo SHE-51A by Fyfe / Epoxy = Tyfo S epoxy by Fyfe.
- GFRP sheet thickness = 0.25 cm. (0.1 in.)

Application

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



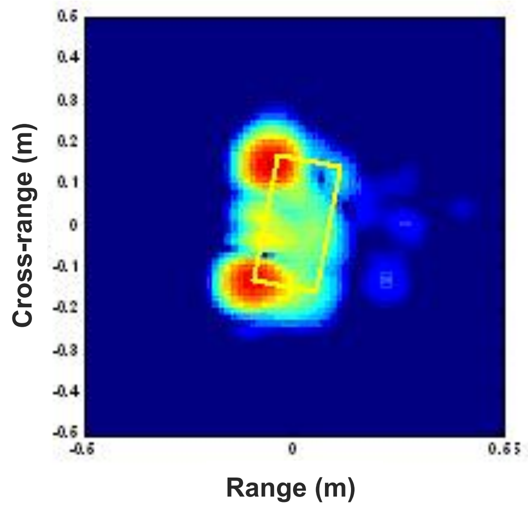
(a) Specimen
– Intact side

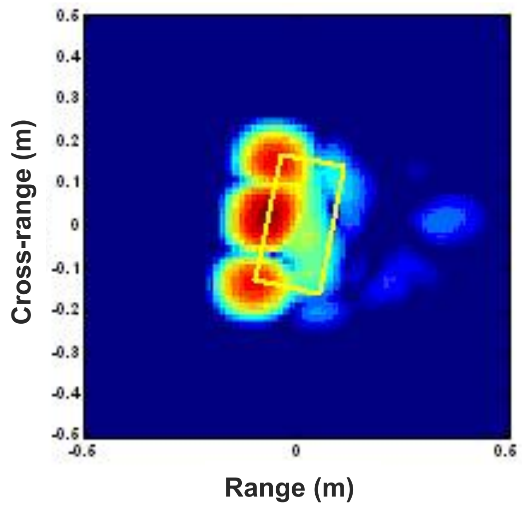


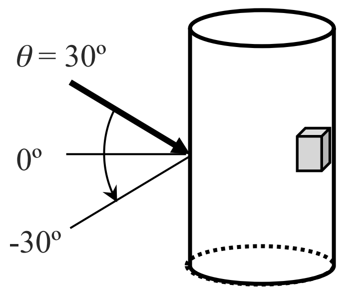
(b) Specimen
– Damaged side

Application

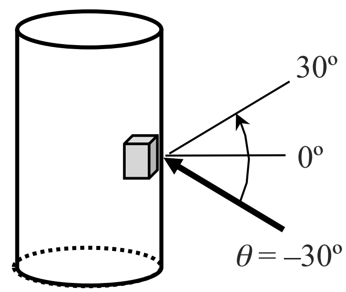
- Reconstructed backprojection images: θ = -10º







(a) Specimen AD1
– Intact side

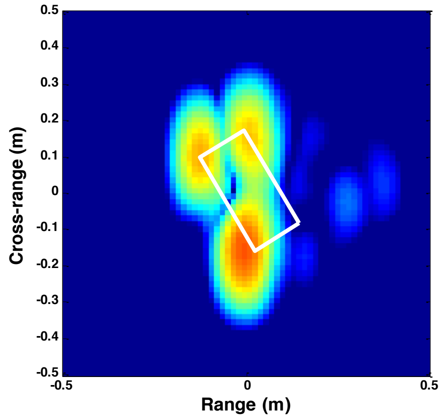


(b) Specimen AD1
– Damaged side

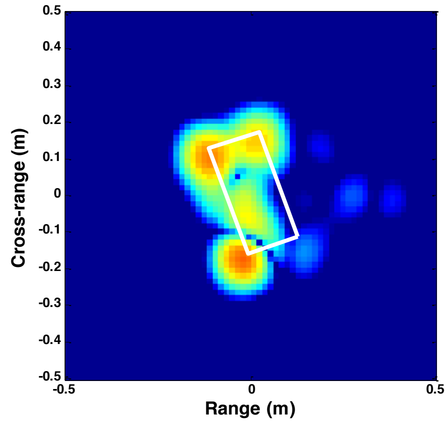
[* Yu, T.-Y., and O. Buyukozturk, *Proc. SPIE 6934*, San Diego, CA, 2008.]

Application

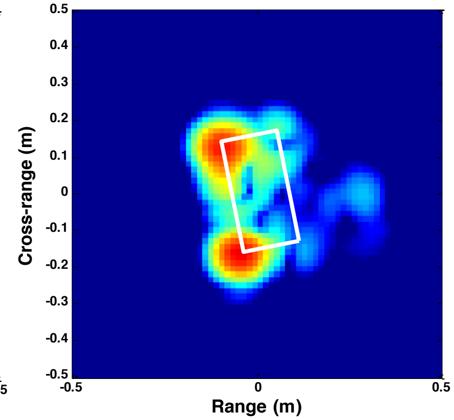
- Effects of incident angle in reconstructed images –



(a-1) 30º

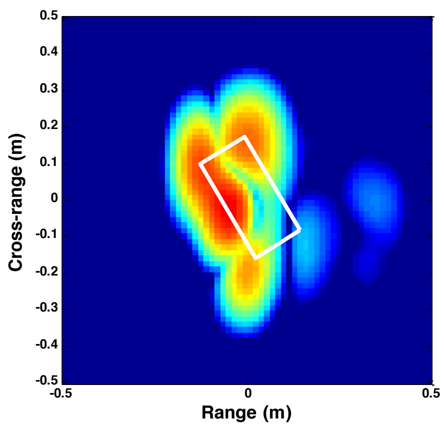


(a-2) 20º

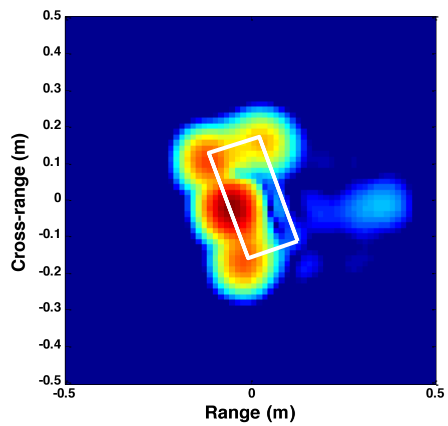


(a-3) 10º

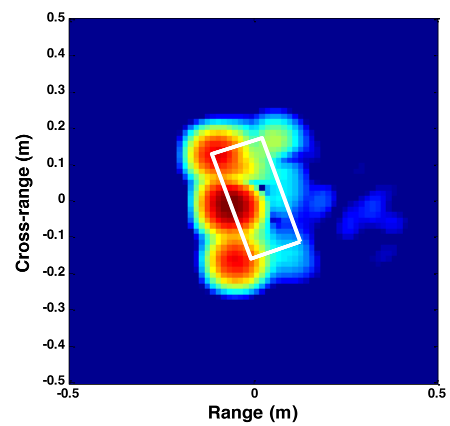
(a) Intact side



(b-1) 30º



(b-2) 20º

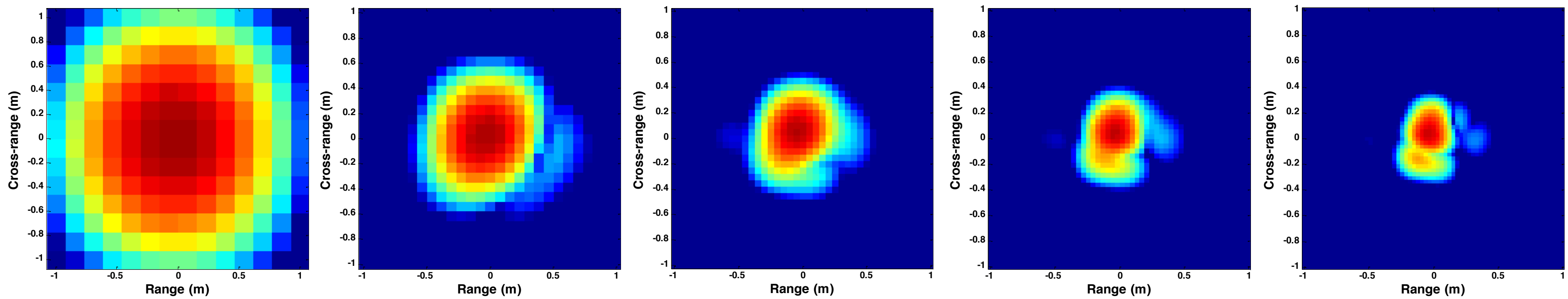


(b-3) 10º

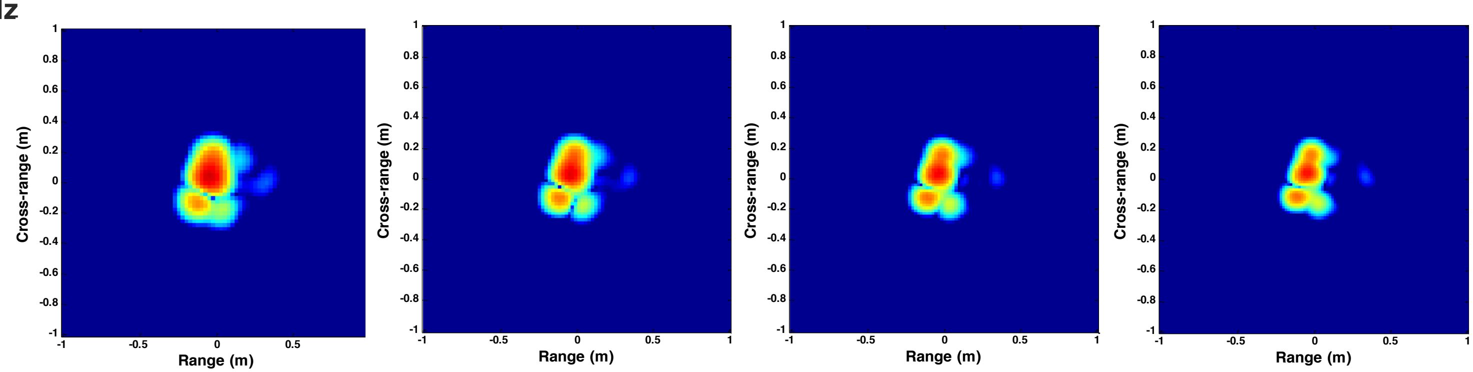
(b) Damaged side

Application

- 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

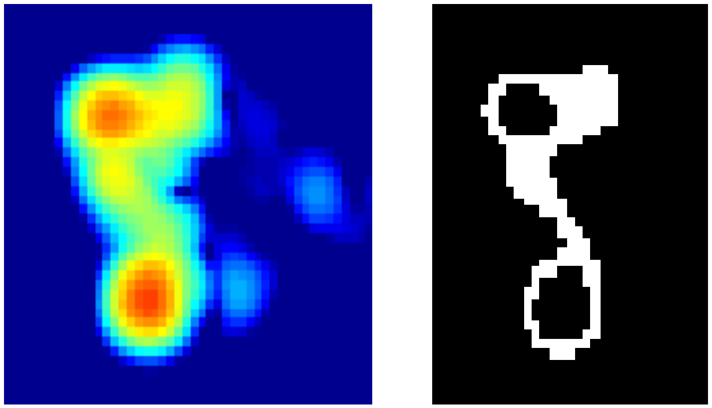


(f) f_c = 9.2GHz, B = 2.4GHz (g) f_c = 9.4GHz, B = 2.8GHz (h) f_c = 9.6GHz, B = 3.2GHz (i) f_c = 9.8GHz, B = 3.6GHz

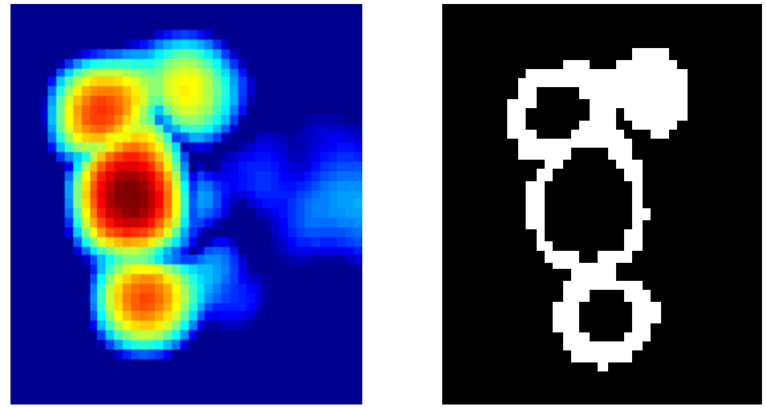
→ Increase used bandwidth = improve image resolutions (range and cross-range)

Application

- Feature-extracted backprojection images



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



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

→ Intact side: $n_E = -1$

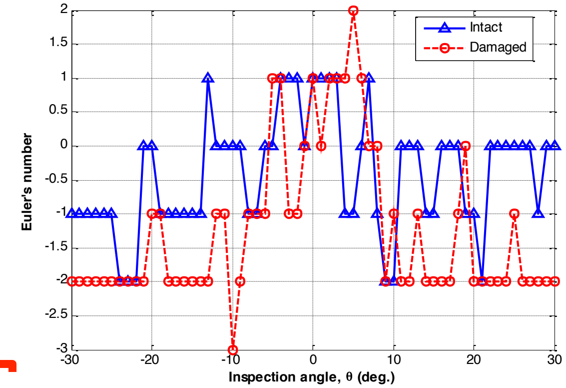
→ Damaged side: $n_E = -2$

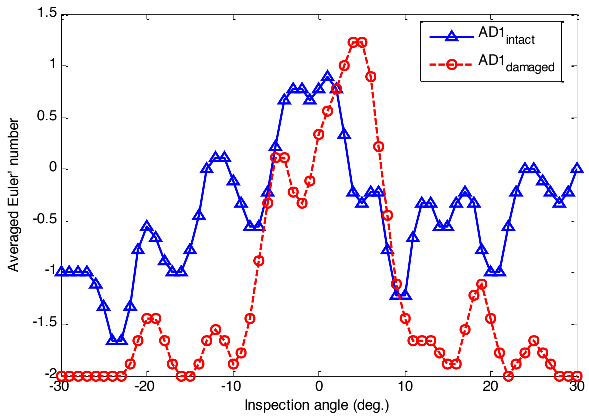
→The more different the Euler's numbers for intact and for damaged sides, the better the detectability.

Application

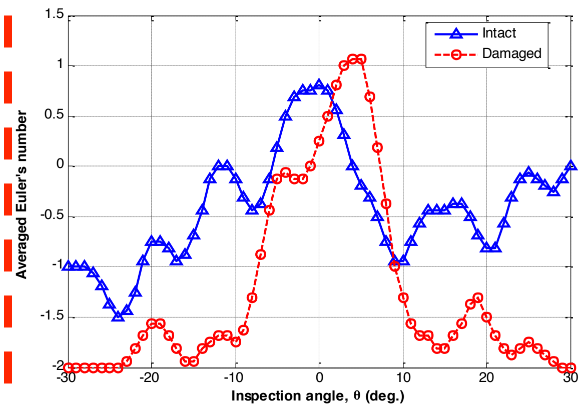
- Raw n_E curves and filtered n_E curves –

Original n_E curves



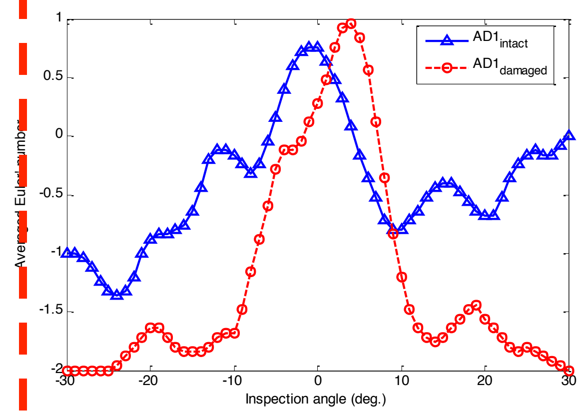


Filtered n_E curves (filter length = 2)



Filtered n_E curves (filter length = 3)

→ *Best result*



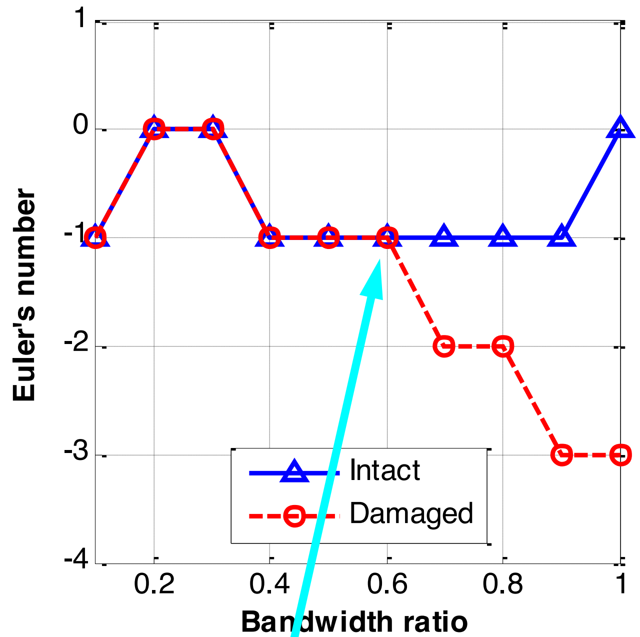
Filtered n_E curves (filter length = 4)

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

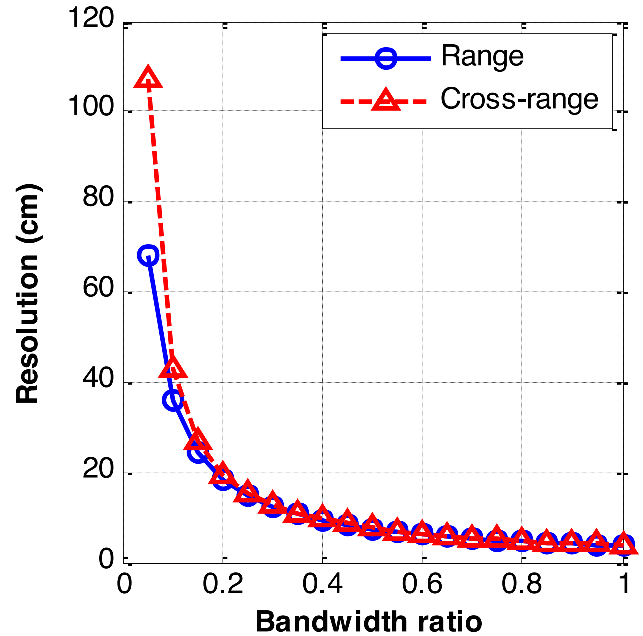
→ *Optimal angle (or angular range) can be quantitatively determined by the maximum differential n_E.*

Application

- 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 Euler's number of damaged structures should be less than the one of intact structures.*

  → *Optimal inspection angle(s) can be determined.*

- 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.*

Acknowledgement

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References

- T.-Y. Yu and O. Buyukozturk, "A distant real-time radar NDE technique for the in-depth inspection of glass fiber reinforced polymer-retrofitted concrete columns," *Proc. SPIE* 6934, San Diego, California, 2008.
- T.-Y. Yu and O. Buyukozturk, "A far-field radar NDT technique for detecting debonding in GFRP- retrofitted concrete structures,*" NDT&E Intl.* 4, pp. 10-24, 2008.
- L. Tsang, J.A. Kong, and K.-H. Ding, *Scattering of Electromagnetic Waves – Theories and Applications*, John Wiley & Sons, New York, 2000.
- M. Soumekh, *Synthetic Aperture Radar Signal Processing with MATLAB Algorithms*, Wiley, New York, 1999.
- J. McCorkle and M. Rofheart, "An order of n2logn backprojection algorithm for focusing wide-angle wide- bandwidth arbitrary-motion synthetic aperture radar," *Proc. SPIE* 2747, pp. 25-36, 1998.
- S. Nilsson and L.-E. Andersson, "Application of fast backprojection techniques for some inverse problems of synthetic aperture radar", *Proc. SPIE* 3370, pp. 62-72, 1998.
- A.F. Yegulalp, "Fast backprojection algorithm for synthetic aperture radar", *Proc. IEEE Radar Conf.*, pp. 60-65, 1999.
- Y. Shirai, *Three-Dimensional Computer Vision*, Springer-Verlag, Berlin, Germany, 1987.
- M. Nixon and A. Aguado, *Feature Extraction and Image Processing*, Newnes, Oxford, UK, 2002.