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
- 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.

[Diagram showing a monostatic radar pointing towards a GFRP-concrete structure with annotations for far-field distance and incident angle.]

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.*
Theory

- Distant ISAR measurement –
  - Time-dependent scattering response of a point scatterer:
    \[ S(\bar{r}_{s,j}, t) = \frac{1}{R_{s,j}^2} \int_{\omega_c - \pi B}^{\omega_c + \pi B} d\omega \cdot \exp[i\omega t] \]  
    (1)
  - Range-compressed scattering response:
    \[ S(\bar{r}_{s,j}, \hat{t}) = \frac{B}{R_{s,j}^2} \exp[i\omega \hat{t}] \cdot \text{sinc}(B\hat{t}) \]  
    (2)
  - Integrated ISAR response:
    \[ D(\xi, \hat{t}) = \int_0^{R_s} d\bar{r}_j \int_0^{2\pi} d\phi_j \cdot G(\bar{r}_j, \phi_j) S(\bar{r}_{s,j}, \hat{t}) \]  
    (3)
Theory

- Backprojection algorithms* –
  - Backprojection image:
    \[ I(\tau, \phi) = \int_0^{R_a \theta_{int}} d\xi \cdot F(\xi, \hat{t}) \]  
    \[ F(\xi, \hat{t}) = C_{bp} \cdot \frac{\partial D(\xi, \hat{t})}{\partial \hat{t}} \]
  - Image reconstruction:
    - Bandpass transformation (\(C_{bp}\) is the backprojection coefficient to yield an ideal bandpass function)
    \[ \frac{\partial D(\xi, \hat{t})}{\partial \hat{t}} = \frac{\partial}{\partial \hat{t}} \int_0^\hat{t} dt' \cdot D(\xi, \hat{t}) \cdot M(\hat{t} - t') = \int_0^\hat{t} dt' \cdot D(\xi, \hat{t}) \cdot \frac{\partial M(\hat{t} - t')}{\partial \hat{t}} \]

Theory

- Morphological processing – To extract and quantify the reconstructed backprojection images
  - Feature extraction:
    - Erosion operator
      \[
      \epsilon_K (I) = \{r | K_r \subset I(x, y) \} 
      \]  
    - Dilation operator
      \[
      \delta_V (I) = \{r | V_r \cap I(x, y) \neq \emptyset \} 
      \] 
  - Feature-extracted images:
    \[
    \hat{I} (x, y | n_{thv}) = \delta_V [ \epsilon_K [ I_{BW} (x, y | n_{thv}) ]] 
    \]  
  - Quantification index: Euler’s number
    \[
    n_E (\theta | n_{thv}) = n_{obj} (\theta | n_{thv}) - n_{hol} (\theta | n_{thv}) 
    \]
Theory

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

\[ n^f_E (\theta) = \sum_{\theta = -\theta_{int}/2}^{\theta_{int}/2} \frac{n_E (\theta)}{L} \]  

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

- Optimization – To yield maximum differential Euler’s number

\[ \Omega_{opt} = \max_{n_E \in \mathbb{Z}} [\Delta n_E (B_{opt}, \theta_{opt})] \]
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), $\theta = -30^\circ$~$30^\circ$, oblique incident scheme

(a) Specimen – Intact side

(b) Specimen – Damaged side
**Application**

- Reconstructed backprojection images: $\theta = -10^\circ$

![Images showing reconstructed backprojection images for Specimen AD1, intact and damaged sides.](image)

\[ \text{[* Yu, T.-Y., and O. Buyukozturk, Proc. SPIE 6934, San Diego, CA, 2008.]} \]
Application

- Effects of incident angle in reconstructed images –

(a) Intact side

(a-1) 30°

(a-2) 20°

(a-3) 10°

(b) Damaged side

(b-1) 30°

(b-2) 20°

(b-3) 10°
Application

- Effects of bandwidth in reconstructed images –

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

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

$\rightarrow$ Increase used bandwidth = improve image resolutions (range and cross-range)
Application

- Feature-extracted backprojection images

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

→ Intact side: $n_E = -1$

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

→ 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)

Filtered $n_E$ curves (filter length = 4)

→ Best result

→ 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 $n_E$. 

17
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.
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References