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

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Outline

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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

We don’t want to see this happen again. But, do we have a solution?
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) ]
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 reliable (inspection results are creditable), efficient (inspection can be accomplished in time) condition assessment technologies for this challenging problem.
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.
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.
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**: 
    \[
    S(\mathbf{r}_{s,j}, t) = \frac{1}{R_{s,j}^2} \int_{\omega_0 - \pi B}^{\omega_0 + \pi B} d\omega \cdot \exp[i\omega t]
    \]  
    \[ (1) \]
  
  - **Range-compressed scattering response**: 
    \[
    S(\mathbf{r}_{s,j}, \hat{t}) = \frac{B}{R_{s,j}^2} \exp[i\omega \hat{t}] \cdot \text{sinc}(B\hat{t})
    \]  
    \[ (2) \]
  
  - **Integrated ISAR response**: 
    \[
    D(\xi, \hat{t}) = \int_{0}^{R_s} d\mathbf{r}_j \int_{0}^{2\pi} d\phi_j \cdot G(\mathbf{r}_j, \phi_j) S(\mathbf{r}_{s,j}, \hat{t})
    \]  
    \[ (3) \]
Theory (cont’d)

- **Backprojection algorithms** –
  - **Backprojection image:**
    \[
    I(\tau, \phi) = \int_{0}^{R_a \theta_{int}} d\xi \cdot F(\xi, \hat{t}) \tag{4}
    \]
  - **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**
      \[
      \frac{\partial D(\xi, \hat{t})}{\partial t} = \frac{\partial}{\partial t} \int_{0}^{\hat{t}} dt' \cdot D(\xi, \hat{t}) \cdot M(\hat{t} - t') = \int_{0}^{\hat{t}} dt' \cdot D(\xi, \hat{t}) \cdot \frac{\partial M(\hat{t} - t')}{\partial t}
      \]

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:**
    \[
    \hat{I} (x, y | n_{thw}) = \delta_V [\epsilon_K [I_{BW} (x, y | n_{thw})]] \quad (7)
    \]

  - **Quantification index: Euler’s number**
    \[
    n_E (\theta | n_{thw}) = n_{obj} (\theta | n_{thw}) - n_{hol} (\theta | n_{thw}) \quad (8)
    \]
Theory (cont’d)

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

\[
n_{E}^{L}(\theta) = \sum_{\theta=-\theta_{\text{int}}/2}^{\theta_{\text{int}}/2} \frac{n_{E}(\theta)}{L} \quad (9)
\]

where \( L \) is the length of the low-pass filter.

- Optimization – To yield maximum differential Euler’s number

\[
\Omega_{\text{opt}} = \max_{n_{E} \in \mathbb{Z}} [\Delta n_{E}(B_{\text{opt}}, \theta_{\text{opt}})] \quad (10)
\]
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), $\theta = -30^\circ$~$30^\circ$, oblique incident scheme

(a) Specimen – Intact side

(b) Specimen – Damaged side
Application (cont’d)

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

[Image of diagrams and graphs showing range and cross-range measurements for intact and damaged sides of Specimen AD1.]

Application (cont’d)

- Effects of incident angle in reconstructed images –

(a) Intact side

(b) Damaged side
Application (cont’d)

- Effects of bandwidth in reconstructed images –

(a) $f_c = 8.2\text{GHz}$, $B = 0.4\text{GHz}$  
(b) $f_c = 8.4\text{GHz}$, $B = 0.8\text{GHz}$  
(c) $f_c = 8.6\text{GHz}$, $B = 1.2\text{GHz}$  
(d) $f_c = 8.8\text{GHz}$, $B = 1.6\text{GHz}$  
(e) $f_c = 9.0\text{GHz}$, $B = 2.0\text{GHz}$  
(f) $f_c = 9.2\text{GHz}$, $B = 2.4\text{GHz}$  
(g) $f_c = 9.4\text{GHz}$, $B = 2.8\text{GHz}$  
(h) $f_c = 9.6\text{GHz}$, $B = 3.2\text{GHz}$  
(i) $f_c = 9.8\text{GHz}$, $B = 3.6\text{GHz}$

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

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 $n_E$. 

Raw $n_E$ curves

Filtered $n_E$ curves (filter length = 3)
Application (cont’d)

- Optimal bandwidth

> 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

- This work was partially supported by NSF CMS-0324607 (2003~2006) for conducting laboratory radar measurements.

- The author would like to express his gratitude to the late Professor Jin Au Kong (Electrical Engineering and Computer Science) at M.I.T. for his encouragements and supports.

- Laboratory radar measurements were conducted by D. Blejer at the M.I.T. Lincoln Laboratory (Lexington, MA).