Array-Measurement-Based Algorithm for Detecting Debonded Regions between Concrete Matrix and Steel Reinforcing Bars in Concrete Samples

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The objective of this study is to develop an array measurement-based algorithm to identify debonded regions between the concrete matrix and steel reinforcing bars of concrete structures. In the proposed procedure, an impact hammer excites one end of a concrete sample and a tri-axial accelerometer is then used to measure the resulting vibration responses on both end surfaces of the sample. Then, a MUltiple SIgnal Classification (MUSIC) algorithm is used to locate the debonded regions as “passive” sources where reflective waves are generated. In order to suppress the effects of the direct waves generated from the excitation as well as the reflective waves from the boundaries at the ends of the sample that make it almost impossible to detect the subtle reflective waves from the debonded region, modified steering vectors are calculated from a finite element model of the sample including the effects of the direct and boundary-reflective waves. Then, the modified steering vectors are used to scan the concrete sample and calculate a 2-D MUSIC

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power map. By applying the proposed algorithm to both experimental and numerical data, it is shown that the proposed algorithm can be used to successfully detect the debonded regions of the concrete sample.

1 INTRODUCTION

Reinforced concrete has been widely used due to its advantages for cost and constructability. Reinforcing steel is typically used for taking tensile loads while a concrete matrix is used for supporting compressive loads but weak under tensile loads. The performance of reinforced concrete relies on the transfer of stresses between the steel and concrete through sufficient bonding of the two materials. Poor construction practices and deterioration processes (e.g., corrosion, alkali-silica reaction, and freeze/thaw) may lead to the debonding between the reinforcing steel and concrete. In order to detect the debonded areas in reinforced concrete samples, Na et al.\textsuperscript{1,2} and Afshari et al.\textsuperscript{3} investigated temporal and spectral data obtained by making ultrasonic wave excitations and measurements on the reinforced concrete samples with various debonded areas. Although they could find the debonded sizes approximately (i.e., the peak amplitudes of 0%, 25%, 50%, and 75% debonded samples were proportional to the debonded sizes), they could not identify the exact debonded locations. Zhu et al.\textsuperscript{4} and Ni et al.\textsuperscript{5} performed two-dimensional (2-D) scanning measurements to identify the debonded locations and size although these measurements require a lot of measurement points.

In this paper, a MUSIC algorithm with modified steering vectors obtained from a Finite Element (FE) model is proposed and applied to experimental data from two samples cast with different cementitious materials. An impact hammer is used to excite each sample and an accelerometer is used to measure the resulting vibration responses at 16 measurement points on both end surfaces of each sample. While a large number of measurement points on entire surfaces are required in conventional 1-D or 2-D ultrasonic scanning procedures, the proposed algorithm is proposed to identify debonded locations and sizes with a small number of measurement points. For the purpose of suppressing the effects of direct excitation wave or reflective waves generated from the boundaries of the samples, the modified steering vectors obtained from the FE model of the sample are used in the proposed MUSIC algorithm. The conventional steering vectors analytically obtained from 1-D free field vibration responses cannot be used to consider the excitation and boundary effects. On the contrary, the proposed steering vectors can account for the excitation and boundary effects by including the excitation force and the finite boundaries in the FE model. The proposed steering vectors are calculated from the FE models with various void sizes and locations. Thus, the MUSIC algorithm with these steering vectors can be used to identify both the debonded sizes and locations.

By applying the proposed algorithm to FE model data generated with 5% error in the concrete modeling parameters, it is shown that the proposed algorithm is robust and does not need accurate estimates of the material properties. Through the experiments with the two concrete samples, it is also demonstrated that the proposed algorithm can successfully identify the location and size of single debonded regions.

2 THEORY

2.1 MUSIC algorithm

The basic idea of an acoustical beamforming procedure is to reconstruct a beamforming power map by comparing acoustic signals “measured” by using an array to “assumed” acoustic
signals radiated from a known free-field source placed at a scanning location. Here, the assumed acoustic signals can be represented as a vector that is referred to as the “steering vector”. When a scanning location is coincident with the location of a “real” source, the beamforming power at this scanning location becomes a local maximum. Since the debonded region of a concrete sample can be regarded as a “passive” source, the debonded region can be thus identified by applying a beamforming algorithm. Amongst various beamforming algorithms, MUSIC algorithm\textsuperscript{6,7,8} is the one of widely used algorithms due to its high spatial resolution.

Temporal signals including the direct waves generated from an excitation and the reflective waves from a debonded region and boundaries are assumed to be measured using \( N \) accelerometers. When the time data measured with the \( n \)-th accelerometer is represented as \( x_n(t) \), \( N \times N \) cross-spectral matrix \( R \) can be calculated after applying the Fourier Transform (FT) to the time data: i.e.,

\[
R(\omega) = X(\omega) \cdot X^H(\omega).
\]  

(1)

For implementing the MUSIC algorithm, the Singular Value Decomposition (SVD) is applied to the cross-spectral matrix in Eqn. (1): i.e.,

\[
R(\omega) = U(\omega) \Sigma(\omega) V^H(\omega).
\]  

(2)

Then, the MUSIC power is calculated at each scanning point as

\[
P_{\text{MUSIC}} = \frac{1}{\sum_{i=p+1}^{N} |g^H \cdot u_i|^2},
\]  

(3)

where \( g \) is the conventional steering vector that is the vector of the acoustic signals at the transducer locations calculated by placing a free-field source at the scanning location, \( u_i \) is the \( i \)-th column vector of the matrix \( U(\omega) \) in Eqn. (2), and \( p \) is the dimension of the signal space. Thus, \( u_{p+1}, u_{p+2}, \ldots, \) and \( u_N \) in the denominator of Eqn. (3) are the noise subspace basis vectors. When the scanning location is coincident to the source location, the inner product between the steering vector and the noise subspace spanned by the basis vectors of \( u_{p+1}, u_{p+2}, \ldots, \) and \( u_N \) in the denominator of Eqn. (3) becomes a small value since they are orthogonal to each other. Then, the MUSIC power is locally maximized at this scanning location. In the next section, the conventional steering vector in Eqn. (3) is replaced with the modified steering vector to enhance the MUSIC algorithm by considering the effects of the direct and reflective waves.

2.2 Modified Steering Vector Based on Finite Element Analysis

The performance of the MUSIC algorithm is strongly dependent on how correctly the real acoustic field of interest can be expressed by an assumed acoustic field. In general, acoustic monopoles and their combinations with anechoic or semi-anechoic boundary conditions are used to generate the assumed acoustic field. However, due to the strong waves generated directly from the excitation and reflected from the boundaries, the subtle reflective waves from the debonded region cannot be separated from the total measured signals to identify the debonded region correctly using the conventional MUSIC algorithm. In order to differentiate the subtle reflective waves from other waves, it is required that the steering vector includes the effects of
the direct excitation as well as the boundaries. Here, it is proposed to calculate the steering vector from a FE model of a concrete sample including the direct excitation and the finite boundaries. In this FE model, an assumed debonded area with various sizes and locations is considered. When the “assumed” debonded size and location coincide with those of a “real” debonded region, the MUSIC power has a local maximum.

As shown in Fig. 1, two-dimensional FE models\(^9,10,11\) are used to calculate the modified steering vector. The length (x-direction) and height (y-direction) of the concrete sample are 1.22 m and 10.2 cm, respectively. In this model, quadratic interpolation functions in each element are implemented (i.e., 2 nodes along one element edge direction), and 97 nodes and 19 nodes are used in the x- and y-directions, respectively. A harmonic excitation with an angular frequency of \(\omega\) is applied to the left end of the reinforced bar and the vibration responses of the concrete sample are obtained by solving the following FE equation\(^10,11\).

\[
Ku + M \frac{\partial^2 u}{\partial t^2} = f, \tag{4}
\]

where \(K\) is the stiffness matrix, \(M\) is the mass matrix, \(u\) is the displacement vector, and \(f\) is the external force vector. In order to represent the debonded area, the density and stiffness of the interfacial elements between the concrete matrix and the steel bar are set to those of the air. The modified steering vectors are calculated from the FE model as a function of frequency, debonded size, and debonded location. In the FE model, free boundary conditions are applied at the end surfaces (i.e., at \(x = 0\) m and \(x = 1.22\) m). Additionally, the amplitude of the excitation force is set to 1 N at each angular frequency since the experimental results are represented as Frequency Response Functions (FRFs) which are the vibration responses normalized with the excitation force signal. The vibration responses are calculated from 4 kHz to 6 kHz with a frequency resolution of 100 Hz. The resulting vibration responses at the accelerometer locations (shown in Fig. 2) are stored as the steering vectors at each set of frequency, debonded size, and debonded location.

3 EXPERIMENTAL SETUP AND DATA PROCESSING PROCEDURE

3.1 Experiments

Figure 2 shows experimental setup, 8 measurement points at one end of a concrete sample, and the formwork and steel bar with a diameter of 0.9 cm used for building the concrete samples. In order to simulate a debonded region, the steel bar is inserted in a 0.305 m long plastic tube with an outer diameter of 1.27 cm. The tube is then glued in place using a silicone sealant (see the white plastic tube in the lower right photo in Fig. 2). One concrete and one mortar samples are built by casting concrete and mortar into the formwork shown in Fig. 2. The mortar sample does not contain any coarse aggregate and is therefore more homogeneous than the concrete sample. The size of the samples is 0.102 m \(\times\) 0.102 m \(\times\) 1.22 m. A Brüel & Kjær (B&K) impact hammer, Type 8206 with a steel tip and a force transducer is used to excite one end of the steel bar. A B&K Pulse system is used to measure acceleration data with a PCB Piezotronics 356A24 accelerometer. Acceleration data at the 16 measurement points, as shown in Fig. 2, are measured on both the end surfaces of the sample and recorded for 0.25 seconds at a sampling frequency of 25.6 kHz.
3.2 Material Properties Estimation

The material properties for the FE models are estimated using the experimental results listed in Table 1. By measuring the weight of the samples, the density of the concrete and mortar can be determined. Then, the natural frequency can be fitted by adjusting the Young’s modulus of the concrete and mortar. The structural damping value is determined by applying the half power bandwidth method to the experimental data. The estimated material parameters are listed in Table 2. Since the volume of the steel bar is significantly smaller than that of the concrete and mortar matrices and the material properties of the steel generally have smaller variation than those of the concrete or mortar, the standard values are used for the steel material as shown in Table 2.

3.3 Modified MUSIC Algorithm Procedure

The 16 measurements on both end surfaces (i.e. \( x = 0, x = 1.22 \text{m} \)) are made through the impact test and the resulting 16 FRFs of the acceleration normalized by the input force are recorded. Then, the \( 16 \times 16 \) cross-spectral matrix in Eqn. (1) is calculated and the SVD procedure in Eqn. (2) is then applied to the calculated cross-spectrum matrix. In order to calculate the modified steering vectors based on the estimated material parameters described in Section 3.2, the vibration responses at the measurement points are obtained from the FE models with various debonded sizes and locations. For example, for a one-element-sized (i.e. \( 2.54 \text{ cm} = 1.22 \text{m}/48 \)) debonded area, acceleration responses are calculated by moving the location of the center of the debonded area from \( x = 1.27 \text{ cm} \) to \( x = 120.7 \text{ cm} \). After increasing the length of the debonded area to the two-element length (i.e. \( 5.08 \text{ cm} \)), the resulting responses are calculated at center locations that range from \( x = 2.54 \text{ cm} \) to \( x = 119.5 \text{ cm} \). The latter procedures are repeated for other length of debonded area. Finally, the steering vectors are obtained as the function of debonded length, location, and excitation frequency. Under this condition, the resolutions of the trial debonded length and location are \( 2.54 \text{ cm} \) and \( 1.27 \text{ cm} \), respectively, which is determined from the element size in the FE model. In addition, the frequency resolution is set to 100 Hz.

By applying the set of modified steering vectors and the noise subspace basis vectors obtained from the experimental data to Eqn. (3), 2-D MUSIC power maps are obtained in the frequency range from 4 kHz to 6 kHz. As described in the previous section, the MUSIC power is locally maximized when the assumed debonded location and size are coincident with the real debonded location and size.

As shown in Fig. 3, the averaged Frequency Response Function (FRF) of a 0.305 m long debonded model is compared with that of a fully-bonded model. At the lower frequencies under 4 kHz, two FRFs are very similar regardless of the debonded region. At the high frequencies above 6 kHz, the auto-spectral amplitude of the impact hammer force in Fig. 4 decreases sharply. In this frequency range, the Signal to Noise Ratio (SNR) is low. Therefore, the measured data below 4 kHz and above 6 kHz are excluded for the data processing.

4 RESULTS

4.1 Simulation Results

The concrete properties in Table 2 are used for two simulation cases. For simulation Case I, a debonded region with the radius from 0.45 cm to 0.635 cm locates at the axial location from \( x = 0.305 \text{ m} \) to \( x = 0.61 \text{ m} \) and the simulation data are obtained by exciting the end of the steel bar
with a force of 1 N at the frequency range of 4 kHz to 6 kHz with the frequency resolution of 100 Hz. Then, the resulting MUSIC power results are linearly averaged over the frequency range. As shown in Fig. 5, the conventional MUSIC algorithm cannot be used to identify the debonded region. In an ideal case where the sample is infinite in its length, the conventional MUSIC algorithm can be used to identify the beginning and ending locations of the debonded region as passive source locations. However, since the boundary reflections at the ends of the sample interfere with the wave signals reflected from the debonded region, the debonded region cannot be identified from the conventional MUSIC result based on the free-field steering vectors.

The modified MUSIC power map in Fig. 6(a) is shown as the function of the assumed center location and length of the debonded region in the x- and y-axis, respectively. The biggest peak can be found at the center location of 0.458 m and the size of 0.305 m. Figure 6(b) shows the cross-sectional view of the 3-D MUSIC power map at the debonded length of 0.305 m. The predicted center location and length are identical to the actual center location (i.e., 0.458 m = (0.305+0.61)/2 m) and length of the debonded region.

In simulation Case II, the effects of errors in the estimated material properties are investigated. In particular, the Young’s modulus and structural damping coefficient are reduced by 5% from the original values although the location and size of the debonded region remains unchanged as in Case I. These underestimated material properties are used to generate acceleration data at the measurement points while the original properties are applied to calculate the modified steering vectors. Although the material properties are slightly biased, the resulting MUSIC power map in Fig. 7 can still be used to successfully identify the location of the center of the debonded area approximately between 0.445 m and 0.483 m and the debonded length estimated to be between 0.305 m and 0.330 m.

4.2 Experimental Results

Figure 8 shows the MUSIC result for the mortar sample calculated by using the actual experimental data and the modified steering vectors obtained from the FE model. The conventional MUSIC result based on the free-field steering vector cannot be used to identify the location and length of the debonded area (see Fig. 8(a)). However, the MUSIC power result obtained by using the proposed steering vectors shows the peak values between 0.419 m and 0.458 m for the center location and 0.280 m and 0.330 m for the debonded length. Since the “actual” center location and length are 0.458 m and 0.305 m, respectively (as indicated by the blue circle in Fig. 8), it can be concluded that the proposed algorithm can be used to estimate the debonded region precisely in case of the mortar sample.

The MUSIC power results for the concrete sample are shown in Fig. 9. Again, the conventional MUSIC power fails to identify the debonded region as shown in Fig. 9(a). In Fig. 9(b), the modified MUSIC power has the peak values approximately between 0.342 m and 0.445 m for the center location and 0.280 m and 0.381 m for the debonded length. Due to the inhomogeneity of the real concrete sample, the predicted debonded size of the concrete sample has a larger difference from the actual size than that of the mortar sample.

5 CONCLUSIONS

In order to non-destructively identify a debonded region in reinforced concrete structures with a relatively small number of measurement points, this paper proposes the modified MUSIC beamforming procedure. An impact hammer test is implemented to excite a concrete sample and measure the resulting acceleration signals on both the ends of the sample. Steering vectors are
calculated from a FE model of the concrete sample built with material properties estimated from the measured data. Then, the proposed modified MUSIC algorithm is applied to the measured data to obtain the 2-D MUSIC power map as the function of the center location and size of the debonded region. By applying the proposed method to the experimental data obtained with reinforced mortar and concrete samples, it is shown that the proposed method can be successfully used to identify the single debonded area of each sample. It is also noted that the accuracy of detection improves with the homogeneity of the matrix. In the near future, the proposed MUSIC method will be validated for a concrete sample with two or three debonded areas and with large-scale reinforced concrete specimens.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


7 TABLES

*Table 1 – Measured values for concrete and mortar samples.*

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<thead>
<tr>
<th>Sample</th>
<th>Mortar</th>
<th>Concrete</th>
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<tr>
<td>Natural frequency [Hz]</td>
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<td>1442.8</td>
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<tr>
<td>Lower and upper half-power frequencies [Hz]</td>
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<td>1430.3, 1454.4</td>
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<tr>
<td>Half-power bandwidth [Hz]</td>
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<td>24.1</td>
</tr>
<tr>
<td>Weight [kg]</td>
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<tr>
<td>Calculated structural damping coefficient</td>
<td>0.0192</td>
<td>0.0167</td>
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*Table 2 – Material properties for concrete, mortar, and steel.*

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<th>Material</th>
<th>Estimated from experiment</th>
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<td>Young’s modulus [Pa]</td>
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<tr>
<td>Density [kg/m³]</td>
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<tr>
<td>Structural damping coefficient</td>
<td>0.0547</td>
<td>0.0324</td>
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</table>

* This value is obtained from Ref. 12.

8 FIGURES

*Fig. 1 – Two-dimensional FE model of concrete sample with steel reinforcing bar.*
Fig. 2 – Experimental setup, measurement points on one end of concrete sample, and formwork and steel bar for building concrete sample. The white plastic tube around the steel bar used to simulate a debonded region is shown in the bottom right photo.

Fig. 3 – Averaged FRFs of both fully-bonded and 0.305 m long debonded FE models.
Fig. 4 – Auto-spectrum of impact hammer’s input force.

Fig. 5 – Conventional MUSIC power normalized with maximum power in linear scale for simulation case I.

Fig. 6 – Modified MUSIC power for simulation case I in dB scale: (a) MUSIC power map and (b) Cross-sectional MUSIC power at debonded size of 0.305 m.
Fig. 7 – Modified MUSIC power for simulation case II.

Fig. 8 – Experimental MUSIC results for mortar sample in dB scale: (a) Conventional MUSIC power and (b) Modified MUSIC power.

Fig. 9 – Experimental MUSIC results for concrete sample in dB scale: (a) Conventional MUSIC power and (b) Modified MUSIC power.