Microwave Cylindrical Reflection Imaging Array
For Structural Damage Detection

Yoo Jin Kim \textsuperscript{a)*}, Luis Jofre \textsuperscript{b)}, Franco De Flaviis \textsuperscript{c)}, and Maria Q. Feng \textsuperscript{d)}

\textsuperscript{a)}Research Associate, Dept. of Civil & Env. Engrg, Univ. of California, Irvine, USA
\textsuperscript{b)}Visitor at UCI & Professor, Dept. of Signal & Comm., Tech. Univ. of Catalonia, Spain
\textsuperscript{c)}Assistant Professor, Dept. of Elect. & Comp. Engrg, Univ. of California, Irvine, USA
\textsuperscript{d)}Associate Professor, Dept. of Civil & Env. Engrg, Univ. of California, Irvine, USA

Abstract: The capabilities of microwave sub-surface imaging system for structural damage detection using cylindrical arrays are described. The analytical expressions of the bifocusing procedures are derived. Finally, reconstruction parameters such as resolution and intensity level are discussed and some images from simulations are also shown.

Key words: Microwave, Cylindrical arrays, Image reconstruction, Damage detection

1. INTRODUCTION

The enhanced structural performance of Reinforced Concrete (RC) columns retrofitted by Fiber Reinforced Polymer (FRP) composite jackets, has been well demonstrated and an increasingly large number of bridge and building columns have been retrofitted with such jackets in the United States and elsewhere. However, seismic damage such as debonding between the jacket and the column that can considerably weaken the column remains a significant concern, as such damage cannot be visually identified. Poor bonding conditions, particularly the existence of large areas of voids and/or debonding, can significantly degrade the structural integrity and safety that could otherwise be attainable by jacketing (Haroun, et al, 1997).

The authors have developed surface imaging techniques using focused microwave in previous work (Feng, et al, 2000b, 2000c, 2000d). In that study, the simulation demonstrated the difficulty in detecting damage by using plane waves. In order to alleviate this difficulty, dielectric lenses were designed and fabricated for focusing microwave on the bonding interface, and three concrete columns were constructed and wrapped with glass-FRP jackets with various voids and debonding conditions. Finally, using the focused microwave surface imaging technique these voids and debonding areas were successfully detected.

In this study, extending an earlier analytical work (Feng et al, 2000a) and preliminary experimental work (Feng, et al, 2000b, 2000c), a microwave sub-surface imaging system using cylindrical array is developed and verified for its capabilities to assess the bonding condition of FRP-jacketed RC columns. The imaging system proposed uses an arrangement consisting of several cylindrical arrayed antennas for transmitting and receiving signals, and a numerical focusing operator is applied to the external signals both in transmitting and in receiving fields. This paper describes a numerical focusing procedure which allows the recovery of a 2-dimensional object from its scattered field.
2. ANALYTICAL FORMULATION

The measurement geometry, shown in Fig.1, uses $N_n \times N_m$ elements, $N_n$ forming a cylindrical transmitting array and $N_m$ forming a cylindrical receiving array. A $N_n \times N_m$ measurement matrix can be obtained as follows: for every selected transmitting element, the receiving array is scanned obtaining an $N_m$-measurement column, then the procedure is repeated for the $N_n$ elements of the transmitting array.

Following the electromagnetic compensation principle, the illumination of an object induces an equivalent electric current distribution, $J_0(x_0, y_0, z_0)$, and this distribution makes electromagnetic image of interest in recovering. The reconstruction algorithm forms every image points by means of the synthesis of two focused arrays (transmitting and receiving arrays), i.e. all the elements of both arrays are weighted by focusing operator so as to be focused on an unique object point. This can be achieved by numerical treatment of the measurement matrix.

The focusing operator can be obtained by taking an inverse of the field induced by a current line. It is well known that the electric fields of the electric line source is proportional to a Hankel function of the second kind whose argument is proportional to the distance from the source to the observation point. Therefore, the incident field at $r_m(x_m, y_m)$ when focusing every transmitting point $r_n(x_n, y_n)$ on the reconstructing point $r_f(x_f, y_f)$ can be expressed as

$$E_f(x_f, y_f) = \sum_{n=0}^{N_n} I_{f_n}(x_f, y_f) \cdot H_0^{(2)}(k_e | r_m - r_n |)$$

where $I_{f_n}(x_f, y_f)$, focusing operator, is given by

$$I_{f_n}(x_f, y_f) = \frac{1}{H_0^{(2)}(k_e | r_m - r_f |)}$$

Using a gel matching cushion with a permittivity constant close to the one of concrete ($\varepsilon_r \approx 5.0$) allows to work directly on a uniform $\varepsilon_r = 5.0$ medium with $k_e = k_0 \sqrt{\varepsilon_r}$.

Scattered field measured at $r_m(x_m, y_m)$ of a defect (object) placed at $r_0(x_0, y_0)$ is

$$E_s(x_m, y_m) = E_0(x_0, y_0) \cdot I_{o_n} \cdot H_0^{(2)}(k_e | r_m - r_0 |)$$

where $I_{o_n}$ is a constant for every object containing its electromagnetic macroscopic characteristics.
When focusing back the received field at $r_m(x_m,y_m)$ on the interest point $r_f(x_f,y_f)$, electromagnetic image of $E_f(x_f,y_f)$ at $r_f(x_f,y_f)$ can be expressed as

$$E_f(x_f,y_f) = \sum_{m} E_r(x_m,y_m) \cdot I_{re}(x_f,y_f)$$

where $I_{re}(x_f,y_f)$, focusing operator, is given by

$$I_{re}(x_f,y_f) = \frac{1}{H_0^{(2)}(k |r_m - r_f|)}$$

Finally, all the process can be grouped as follows:

$$E_f(x_f,y_f) = \sum_{m} \left[ \frac{1}{H_0^{(2)}(k |r_m - r_f|)} \cdot \sum_{i} I_{obj} \cdot H_0^{(2)}(k |r_m - r_{obj,i}|) \cdot \sum_{j} \frac{1}{H_0^{(2)}(k |r_m - r_{obj,j}|)} \right]$$

or

$$E_f(x_f,y_f) = \begin{bmatrix} I_{r_1} & I_{r_2} & \ldots & I_{r_n} \\ \vdots & \vdots & \ddots & \vdots \\ I_{r_{j,1}} & I_{r_{j,2}} & \ldots & I_{r_{j,n}} \end{bmatrix} \begin{bmatrix} E_{s,r_1} & E_{s,r_2} & \ldots & E_{s,r_n} \\ \vdots & \vdots & \ddots & \vdots \\ E_{s,jr_1} & E_{s,jr_2} & \ldots & E_{s,jr_n} \end{bmatrix} \begin{bmatrix} I_{r_1} \\ \vdots \\ I_{r_n} \end{bmatrix}$$

3. Reconstruction Parameters

The formulation derived in the previous section has been applied to the case of two cylindrical arrays of 32 antennas each, with frequency of 10 GHz ($\lambda_0 = 3cm, \lambda_e = 1.34cm$). Fig. 2 (a) and Fig. 2 (b), respectively, show the focusing intensity of transmitting and receiving arrays when focusing on the location of $(\rho=0.20m, \phi=0^\circ)$.

In order to study the focusing capability of the system at different distances of the array and angular points of view, nine point-like objects have been placed at boundary and central landmark points of the reconstructing 2D cross section. The results, as shown in Fig. 3, show a good uniformity of the 9 point focusing intensity level and impulse response shape that suggest a very good behavior of the reconstruction algorithm in real conditions of extended damage areas, noise, and measurement errors.

Finally, simulations have been conducted in order to verify the resolution capabilities of the system. The results show that the system, due to the fact of focusing both transmitting and receiving arrays, is able to obtain resolutions in the order of wavelength in the
dielectric medium. That clearly improves the resolution obtained with a conventional mono-focusing receiving system.

![Image of 9 Point-Like Objects (Impulse Response of the System)](a) X-Y Plane Image  (b) 3-D Image

Fig. 3  Image of 9 Point-Like Objects (Impulse Response of the System)

![Reconstructed Image of Two Point-Like Objects (Resolution of the System)](a) Transverse Distance of 0.01346 m  (b) Longitudinal Distance of 0.01346 m

Fig. 4  Reconstructed Image of Two Point-Like Objects (Resolution of the System)

4. CONCLUSION

In this study, the capabilities of microwave sub-surface imaging system using cylindrical reflection arrays are verified. The simulation results show that the reconstruction algorithm gives a uniformity of focusing intensity level and the resolution can be improved by focusing both in transmitting and receiving arrays.

5. REFERENCES