EDDY CURRENT SENSOR ARRAY. APPLICATION TO NONDESTRUCTIVE EVALUATION OF CARBON-EPOXY COMPOSITES

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ABSTRACT
This paper presents the functioning of an eddy current sensors array, made from a rectangular emission coil inside whom reception sensors are disposed under the shape of a rectangular lattice. The signals delivered by the sensors from array are post processed using a super-resolution procedure. Thus, a substantial improvement of signal to noise ratio is obtained. The sensors array is used to examine carbon epoxy plates to detect delaminations and fiber breaks.

1. INTRODUCTION

Since the 1970's, the advanced composites have been used (and often exceeded expectations) as primary and secondary structure on new aircrafts. Although spearheaded by the military, composite conversion was often an arduous process because of the initial high cost of the materials, limited design expertise and misconceptions from designers who were slow to be "converted". The advantages in using carbon epoxy composites are listed below [1]:

- Typically composites can provide a weight saving between 25 and 50 percent over an aluminum structure;
- Specific tensile strength (ratio of material strength to density) is four to six times greater than aluminum or steel;
- Specific modulus (ratio of material stiffness to density) is three to five times greater than aluminum or steel;
- Composites are more versatile than metals and can be tailored to meet performance needs and complex design;
- Excellent structural damping properties can be designed into carbon epoxy composites;
- Fatigue and fracture resistance are superior approaching 60 percent of ultimate strength (considerably higher than aluminum and steel).

The composites structures can possibly have the damages under the impact and fatigue load. The damage which occurs inside the structures cannot be easily observed and therefore the size of the overall damage may be underestimated. Accordingly, accurate evaluation for the

damages in the structures with composites which show very complicated mechanically behavior is very important for safe designing and, also, for life time prediction.
The carbon-epoxy composites have electric properties that depend on the type of carbon fibers and on their volume fraction in the material, having the transverse electric conductivity between 10 and 100 S/m, and the longitudinal conductivity ranging between $5x10^3$ and $5x10^4$S/m. In the case of low energy impacts, the composite will be elastically deformed and no local alteration of the electric conductivity occurs. In the same time, desbonding on small zones of the reinforcing fibers from the resin epoxy matrix can appear.
The impacts of small energy would be- in principle- detected by ultrasound procedures, such as acoustic microscopy [2], but cannot be emphasized by electromagnetic methods [3]. For high energy impacts, the local deformation results in delamination, deviation and /or breaking of the carbon fibers. In this case, local modifications of the electric conductivity can occur, and can be detected by eddy current methods (EC) [4] and ultrasound methods [5].
The objective of the non-destructive testing is to develop a fast, reliable and effective cost technique for detecting defects in materials under a variety of operating conditions. For electrically conducting materials, structures, and subassemblies, eddy current inspection is typically imposed for maintaining specified quality standards and product norms. The development of advanced diagnostic systems that are able to detect and identify material degradation in the structures of carbon epoxy composites is a new challenge for the non-destructive evaluation.
This paper presents the design of a new EC sensor based on a two dimensional array of coils, a super-resolution algorithm for improving the detection and characterization of the degradation. A computational model of the array is derived using dyadic Green's function and volume integral method. The sensor is then applied at non-destructive evaluation of carbon epoxy composites plates impacted at low energy.

2. SENSOR ARRAY MODEL

A model for the operation of the sensor array can be developed using the dyadic Green's function [6] and the volume integration method. The fields produced by a rectangular transmission coil of dimension 2ax2b, cross section $\varepsilon_1 x \varepsilon_2$ and having N_S turns, through which a current of the angular frequency ω and amplitude I_0 circulates, is given by

$$\overline{E}_0(\overline{r}) = j\omega\mu_2 \int_{Vsource} \overleftrightarrow{G}_{12}(\overline{r},\overline{r}')\overline{J}(\overline{r}')d\overline{r}' \tag{1}$$

where $\overline{J}$ is given in [7] as

$$\begin{aligned} J_x &= I_0 e^{-j\omega t} \int_{d-\frac{\varepsilon_2}{2}}^{d+\frac{\varepsilon_2}{2}} \delta(z-z_0)dz_0 \left[\int_{a-\frac{\varepsilon_1}{2}}^{a+\frac{\varepsilon_1}{2}} \delta\left(y+y_0\right)dy_0 - \int_{-(a+\frac{\varepsilon_1}{2})}^{-(a-\frac{\varepsilon_1}{2})} \delta\left(y-y_0\right)dy_0 \right] \int_{-b_1}^{b_1} \delta\left(x-x_0\right)dx_0 \\ J_y &= I_0 e^{-j\omega t} \int_{d-\frac{\varepsilon_2}{2}}^{d+\frac{\varepsilon_2}{2}} \delta(z-z_0)dz_0 \left[\int_{b-\frac{\varepsilon_1}{2}}^{b+\frac{\varepsilon_1}{2}} \delta(x-x_0)dx_0 - \int_{-(b+\frac{\varepsilon_1}{2})}^{-(b-\frac{\varepsilon_1}{2})} \delta(x+x_0)\ dx_0 \right] \int_{-a_1}^{a_1} \delta\left(y-y_0\right)dy_0 \\ J_z &= 0 \end{aligned} \tag{2}$$

where *d* represent the height according to a X,Y Cartesian coordinate plane.

When the plane of the sensor surface is parallel to the sample surface, the field produced will be transverse electric (TE). When the tested object is flat, with finite width, the expression of the dyadic Green's function $\vec{G}_{12}$ (source in air (1) and the observation point in the material (2)) in Fourier space is

$$\tilde{\tilde{G}}_{12} = \frac{j}{8\pi^2} \begin{pmatrix} k_y^2 & -k_x k_y & 0 \\ -k_x k_y & k_x^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} F_-(z,z') \frac{1}{k_{1z} k_s^2} \exp\left(jk_x (x-x') + jk_y (y-y') \right) \quad (3)$$

where

$$F_-(z,z') = \left[e^{-jk_{2z}z} + e^{jk_{2z}(z+2d_2)} \tilde{R}_{23} \right] e^{jk_{2z}d_1} \tilde{T}_{12} e^{-jk_{2z}d_1} e^{jk_{1z}z'} \tilde{M}_2 \quad (4)$$

with

$$\tilde{M}_2 = \left[1 - \tilde{R}_{23} \tilde{R}_{21} e^{2jk_{2z}(d_2-d_1)} \right]^{-1} \quad (5)$$

$$k_{1z} = \left(k_1^2 - k_s^2 \right)^{1/2}; \quad k_{2z} = \left(k_2^2 - k_s^2 \right)^{1/2}; \quad k_1^2 = \omega\mu_1 \left(\varepsilon_1 + j\frac{\sigma_1}{\omega} \right); \quad k_2^2 = \omega\mu_2 \left(\varepsilon_2 + j\frac{\sigma_2}{\omega} \right),$$

$\tilde{T}_{12}$ and $\tilde{R}_{23}$ are the generalized transmission and reflection coefficients respectively [6], d_1 and d_2 are the distances from the X,Y plane to the upper and lower surfaces of the test plate. The region of interest in the material is discretized into $N_x \times N_y \times N_z$ identical cells of dimensions $\Delta x \times \Delta y \times \Delta z$, small enough so that the field in the cell is approximated by the field at the centre of the cell. The equations are discretized using the point-matching variant of the moment method [8]. The presence of material discontinuities is equivalent to an auxiliary current source that creates the field described by the dyadic Green's function $\vec{G}_{22}(\bar{r},\bar{r}')$. Due to the TE character of the field, $\vec{G}_{22}(\bar{r},\bar{r}')$ there are no singularities, so that the integrals over the volume of the defect will be well defined.

In the Fourier space, the dyad $\vec{G}_{22}(\bar{r},\bar{r}')$ is

$$\tilde{\tilde{G}}_{22} = \frac{j}{8\pi^2} \begin{pmatrix} k_y^2 & -k_x k_y & 0 \\ -k_x k_y & k_x^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} F_\pm(z,z') \frac{1}{k_{2z} k_s^2} \exp\left(jk_x (x-x') + jk_y (y-y') \right) \quad (6)$$

where

$$F_+(z,z') = \left[e^{-jk_{2z}z'} + e^{jk_{2z}(z'+2d_2)} \tilde{R}_{23} \right] \left[e^{jk_{2z}z} + e^{-jk_{2z}(z+d_2)} \tilde{R}_{12} \right] \tilde{M}_2 \text{ for } z>z'$$

$$F_-(z,z') = \left[e^{jk_{2z}z'} + e^{-jk_{2z}(z+2d_1)} \tilde{R}_{21} \right] \left[e^{-jk_{2z}z} + e^{jk_{2z}(z+d_2)} \tilde{R}_{23} \right] \tilde{M}_2 \text{ for } z<z'$$

The dyad $\vec{G}_{22}$ is analytically integrated on the cell volume. For the case z = z', the value is given by

$$\int_{z_p+\frac{\Delta z}{2}}^{z'} G_{22_{lm}}^{+} dz' + \int_{z'}^{z_p+\frac{\Delta z}{2}} G_{22_{lm}}^{-} dz' \quad (7)$$

where z_p is the z coordinate of the p[th] cell centre, $l,\ m \in \{x,y,z\}$, $G_{22_{lm}}^{+}$ is the expression for z>z' and $G_{22_{lm}}^{-}$ for z<z'. In the presence of a discontinuity in the material with the conductivity σ_f, the field in the material will be

$$\bar{E}_2(\bar{r}) + j\omega\mu_2\sigma_2 \int_{Vflaw} \vec{\vec{G}}_{22}(\bar{r},\bar{r}')\bar{E}_2(\bar{r}')\left[\frac{\sigma_f(\bar{r}')}{\sigma_2}-1\right]d\bar{r}' = \bar{E}_0(\bar{r}) \qquad (8)$$

To obtain $\bar{E}_2(\bar{r})$, the discretized variant of the Fredholm equation was solved using the Moore-Penrose inversion [9]. The perturbation field in air due to the discontinuity is

$$\bar{E}_1(\bar{r}) = j\omega\mu_2\sigma_2 \int_{Vflaw} \vec{\vec{G}}_{21}(\bar{r},\bar{r}')\bar{E}_2(\bar{r}')\left[\frac{\sigma_f(\bar{r}')}{\sigma_2}-1\right]d\bar{r}' \qquad (9)$$

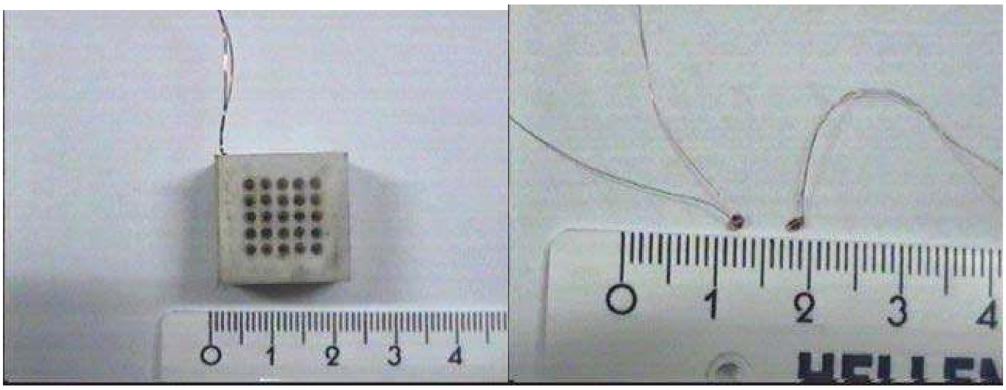
and the induced electromotive force in one receiver coil will be given by

$$e(\bar{r}) = \oint_C \bar{E}_1(\bar{r})d\bar{r} \qquad (10)$$

where C is the contour of the receiver coil. The expressions of $\vec{\vec{G}}_{21}$ components are obtained using similar procedures.

3. EXPERIMENTAL SET-UP

The 2D eddy current sensor array has the physical realisation presented in Figures 1a and 1b.



a. b.

Figure 1. 2D 5 x 5 eddy current sensor array:
a. Frontal view ; b. Reception coils

The transmitter coil has 100 turns and has the dimension 20x20 mm^2. The receiver consists of a two dimensional 5x5 array of identical coils each having an outer diameter of 2 mm, and the distance between the centres of the coils is 2.4 mm. The sensor coils are connected to the measurement equipment as shown in Figure 2.

The AWG 7223PC function generator is used for generating the excitation signal. The lock-in amplifier type SR 844 made by Stanford Research Industries USA measures the output of the receiver coils and is connected to a PC through an IEEE 488 interface. The reception coils are periodically interrogated using an electronic multiplexer also controlled by the PC.

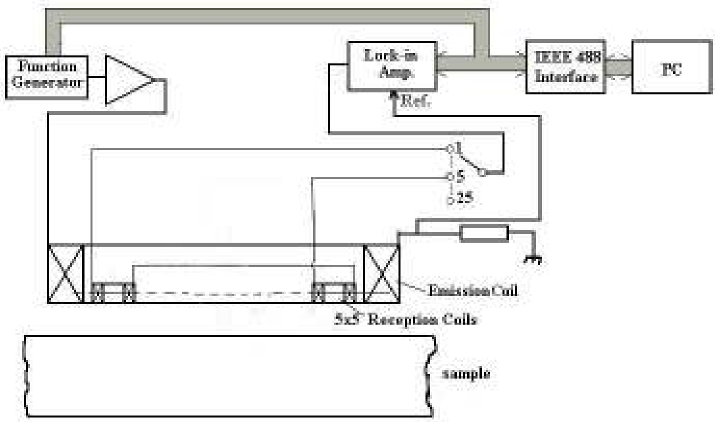
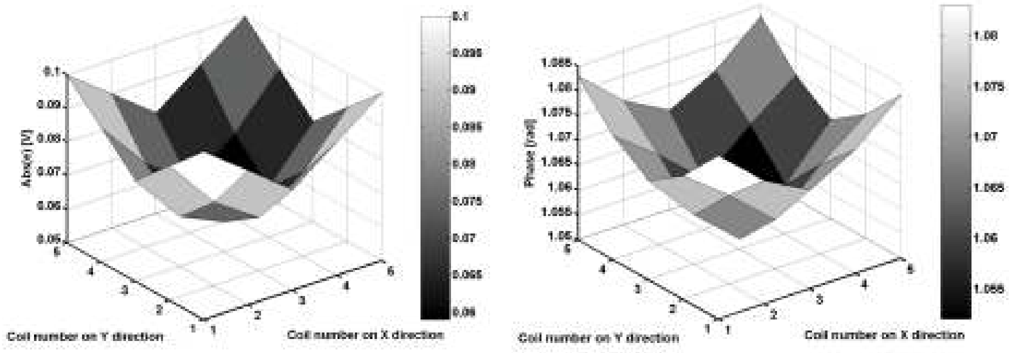


Figure 2.Experimental set-up

4. SIMULATION RESULTS

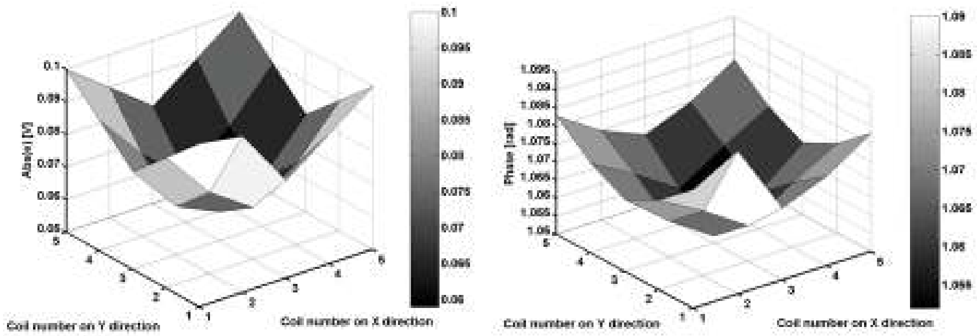
The response is measured placing the sensor over the surface of a carbon-epoxy composite plate. For a composite plate having 48 carbon fibres plies with the orientation $\left[-45^0_2, 0^0_2, 45^0_2, 90^0_2\right]_S$ and total thickness of 6mm, the response of arrays at 300 kHz and 0.1 A amplitude of the excitation current, are presented in Figure 3.



a. b.

Figure 3. The response of the eddy current sensor array placed on a carbon epoxy composite plate; frequency – 300 kHz, amplitude - 0.1A; lift-off – 1 mm
a. amplitude response; b. phase response.

The response represents the reflection of the electromagnetic field created by the emission part of the transducer on the composite plate, and receiving by the 2D array of reception coils. In Figure 4, the response in amplitude and in phase of the array are presented for the case in which two small delamination are induced by introduction of two 2 x 2 mm^2 Teflon foils of 0.1 mm thickness between the 2th and the 4th plies in the fabrication process of the carbon epoxy plate. The distance between the centers of two foils has been 2.4 mm. The arrays are placed in the manner in which the two delamination centers correspond exactly to the centers of the reception coils indexed (5, 2) and (4, 4).



a. b.

Figure 4. The array response for two delaminations with the dimension $2 \times 2\ mm^2$ placed under coils (5, 2) and (4, 4).
a. amplitude response; b. phase response

The resolution of the eddy current sensor array can be substantially improved by using super-resolution procedures.

5. SUPER-RESOLUTION PROCEDURE

The super- resolution procedures are currently used in the applications as sonar and radar. As it can be observed in Figure 3, although the array has been placed over a composite plate considered as being homogeneous, without delaminations, fibre breakings, etc., that might lead to local modifications of the electrical conductivity, due to the distribution of electric field created by the emission coil of the array, the signals provided by reception coils of the array are not equal in modulus and phase. From this reason, we will introduce a weight matrix for the amplitude and the phase of each reception coil from the array, depending of its position.

The role of the weight matrix is double:

- It assures equal amplitudes and phases for the electromotive forces induced in the reception coils of the array when it is placed on a material's uniform region, or when the same discontinuity is placed exactly below the centre of the coils from array.
- It eliminates the possibility of appearance of the 1^{st} rank ambiguities that might happen when a discontinuity can be found between the coils from array, providing in this way-information to many more reception coils.

We note with w_{ij}, the value of weight corresponding to the coil of which centre is indexed by the pair (i, j).

We define the beamformer's output signal for the reception coil indexed (i, j) to be

$$z_{ij} = w_{ij} \cdot y_{ij} \tag{11}$$

where z can be the amplitude or the phase output, y can be amplitude or phase of e.m.f induced in the reception coil. The weight matrix of the array can be written:

$$w = \begin{pmatrix} w_{11} & w_{12} & .. & w_{N} \\ w_{21} & w_{22} & .. & w_{2N} \\ : & : & :: & : \\ w_{M1} & w_{M2} & .. & w_{MN} \end{pmatrix} \tag{12}$$

where M and N represent the number of rows and columns, respectively, of the uniform arrangement of reception coils that form the sensor array.
We define the sensibility matrix of the array as being:

$$\overline{A} = \overline{w} * \overline{w}^H \tag{13}$$

where the superscript H represent the hermitic matrix (transpose conjugate of the matrix).
We can define a new matrix S, as being:

$$\overline{S} = \overline{A}\left(\overline{A}^H \overline{A}\right)^{-1} \overline{A}^H \tag{14}$$

where the superscript "-1" represent the inverse of the matrix.
The auto-correlation matrix of the response signal can be defined as:

$$\overline{R}_{xx} = \overline{z} * \overline{z}^H \tag{15}$$

The super-resolution method uses the maximum likelihood estimation procedure [17] for the case of coherent sources. The source locations are estimated to lie at the points in space where the function $(\overline{S} * \overline{R}_{xx})$ is maximal. The use of the super resolution method can lead simultaneous to the improvement of the signal to noise ratio (SNR), too. The SNR is defined to be the ratio of the mean square value of the signal and noise components, which conceptually expresses the ratio of the signal and noise powers. If a single sensor was located at the spatial origin, its response to a noise corrupted signal would be

$$y(t) = s(t) + n(t) \tag{16}$$

where n represents the noise field. This noise may be attributed to the sensor (thermal noise in its electronics, for example) or to the background radiation.

$$SNR_{sensor} = \frac{\varepsilon\left[s^2(t)\right]}{\varepsilon\left[n\ (t)\right]} = \frac{R_s}{R_n} \tag{17}$$

where R_s and R_n denote the signal's correlation function and the noise correlation function.
The array gain G is defined as the ratio of the array signal to noise ratio and the sensor signal to noise ratio

$$G \equiv \frac{SNR_{array}}{SNR_{sensor}} \tag{18}$$

If we assume that the noise is uncorrelated spatially from sensor to sensor, we find that the expression of the unnormalized mean square value of the signal term equals $R_s\left|\sum_{i=1}^{N}\sum_{j=1}^{M} w_{ij}\right|^2$ and the expression for unnormalized mean square noise power in the array output becomes $R_n \sum_{i=1}^{N}\sum_{j=1}^{M}\left|w_{ij}\right|^2$. In this case, the array signal to noise ratio becomes

$$SNR_{array} = \frac{R_s\left|\sum_{i=1}^{N}\sum_{j=1}^{M} w_{ij}\right|^2}{R_n \sum_{i=1}^{N}\sum_{j=1}^{M}\left|w_{ij}\right|^2} \tag{19}$$

and, the array gain can be written as

$$G = \frac{\left|\sum_{i=1}^{N}\sum_{j=1}^{M} w_{ij}\right|^2}{\sum_{i=1}^{N}\sum_{j=1}^{M}\left|w_{ij}\right|^2} \tag{20}$$

Introducing in the equation (20) the values used for the weight matrix of our sensor array, we will obtain an array gain G=0.7*N*M, that will lead to a substantial improvement of the signal to noise ratio, in comparison with the one of an individual sensor array.
Applying the super resolution method developed above to the synthetic data (the data obtained as a result of numerical simulation) presented in Figure 4, the answer of the sensor array will be obtained (Figure 5) .

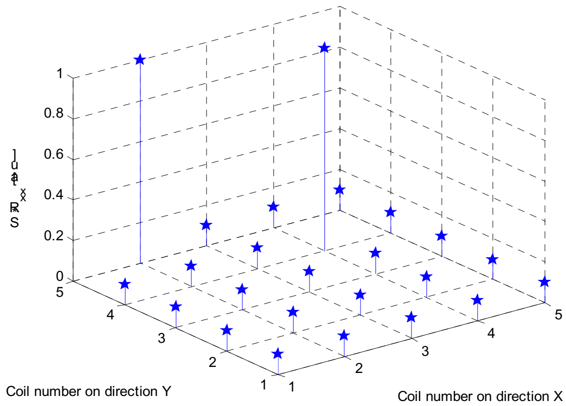


Figure 5. The answer of the sensor array

The maximum values correspond to the positions of the two delaminations that are placed under the coils indexed with (4, 4), (5, 2). Taking into analysis Figure 5, it can be clearly observed that the two small dimension delaminations were clearly and correctly indicated by the area, using the procedure of super resolution for the data post- processing.

6. EXPERIMENTAL RESULTS

Experimental measurements have been made on carbon-epoxy composite plates that had two types of defects:
- delaminations made by the inserting Teflon thin layer pieces with the dimension of 2x2x 0.1 mm^3 between the plies of the carbon fibers during the fabrication of the plates;
- inserting the carbon fibers transversally sectioned which will simulate the fiber breaking that might appear especially due to impacts with relatively high energies;

In Figure 6 we present the real answer of eddy current sensor arrays for the case of two delaminations induced in the manner described above. The array has been placed so that the situation shall correspond to the simulated one and presented in Figure 4 a, b and Figure 5.
The answer of the eddy current sensor array after the signal post-processing of the two delaminations of 2x2 mm^2 placed below the centers of the coils (4, 4) and (5, 2) from array.
Examining the data presented in Figure 5, it can be observed that even in the case of the effective examination of the carbon-epoxy composite plates with delaminations, the position of these can be clearly emphasized. It has be mentioned that the direction of the carbon fibers

due to the modification of their orientation as a consequence of inserting the Teflon pieces that simulate the delaminations, is not visible.

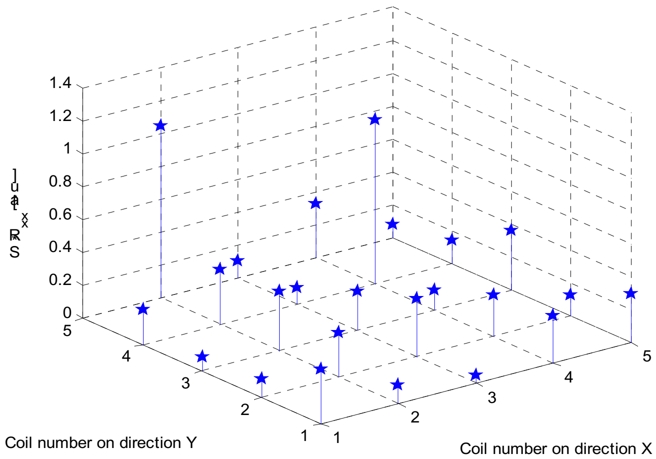


Figure 6. The real answer of eddy current sensor arrays

Placing the sensor area on a zone of the material in which the carbon fibers are orderly distributed, and using the super resolution procedure described above, the image of the fibers begins to be visible with the direction of 45^0, situation presented in the Figure7.

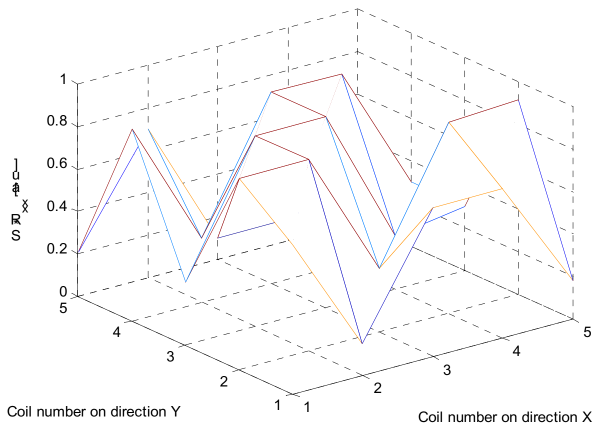


Figure 7. The answer of eddy current sensor on a zone belonging to the carbon-epoxy composite plate with orderly fiber structure..

Placing the eddy current array on a region of composite where there have been intentionally introduced sectioned carbon fibers, and applying the same procedure of super resolution, the zone in which the fibers have been sectioned transversally will become visible, situation presented in Figure 8.
Even in this situation, the use of the eddy current sensor arrays and the data post processing using the procedures of super resolution will lead to the detection of the regions from the carbon- epoxy plates where carbon fibers breaking can be found.

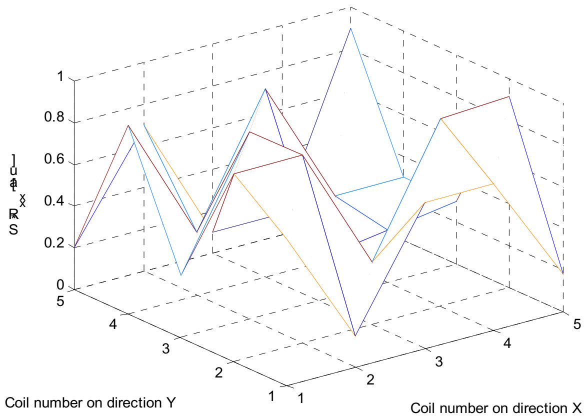


Figure 8.The answer given by the eddy current sensor array for a region of material in which sectioned carbon fibers exist.

7. CONCLUSIONS

The eddy current sensor arrays prove their utility in the case of the carbon epoxy composite materials examination, too. The utilization of the sensor arrays, and the super resolution procedures as the signal post processing method, will lead us to an improvement of the signal to noise ratio reported to the situation in which it is used only one sensor for the control.
Small dimension delaminations and the carbon fiber breakings can be emphasized.

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REFERENCE:

1. ASME Handbook volume 21 : Composites, ASME International, N.J., 2001
2. X.E.Gros, K.Ogi, K.Takahasi – Ultrasound C-scan and scanning acoustic microscopy testing of delaminated quasi-isotropic CFRP materials: A case study, J. of Reinforced Plastics and Composites, 17,(1998), pp.389-405
3. R.Grimberg, D.Premel, M.Lemistre, D.Balageas, D.Placko, Compared NDE of damage in graphite epoxy composites by electromagnetic methods, Proceedings SPIE, vol. 4336, V.George and col. (eds.), 2001
4. R.Grimberg, A.Savin, R.Steigmann, A.Bruma, Eddy current examination of carbon fibers in carbon epoxy and Kevlar, Int. J. of Materials and Product Technology,27,(2006),pp.221-228
5. Report of American Institute of Aeronautics and Astronautics, ANSI/AIAA S – 081A-2006 – Space systems – Composite Overlapped Pressure Vessels, Reston,VI, 2006
6. W.C.Chew, Waves and fields in inhomogeneous media, Van Nostrand Reinhold, N.Y., 1990
7. R. Grimberg, A.Savin, E.Radu, O.Mihalache, Nondestructive Evaluation of the Severity of Discontinuities in Flat Conductive Materials Using the Eddy Current Transducer with Orthogonal Coils, IEEE Trans on Mag. 36, 1, (2000), 299-307 R.F.Harrington, Field computation by moment method, McMillan Comp. London, 1967
8. J.C.Nash, Compact numerical methods for computers – linear algebra and function minimization, 2-nd ed., Adam Hilger, N.Y., 1990
9. S.V.Shell, V.A.Gardner, High resolution direction finding, in Handbook of Statistics vol. 10, R.C.Rao (eds.), Elsevier, Amsterdam, 1993, pp.755-817