Electromagnetic sensor using metamaterials for nondestructive evaluation

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Abstract. This paper proposes to present the results obtained in NDE of metallic strip gratings and carbon fiber reinforced plastics (CFRP) composite materials that can be considered as multilayered strip gratings structures due to the carbon fiber conductivity. The possibility to manipulate the evanescent waves that appear in the space between carbon fibers or in slits of metallic strip gratings, using electromagnetic sensor with metamaterial lens allows a spectacular improvement of the spatial resolution, leading to detection of interruption, short circuits of metallic strips in printed circuit boards as well as nonalignment of carbon fibers, lack of resin or voids as well as delamination induced by low energy impacts.

1. Introduction

The electromagnetic methods for nondestructive evaluation (NDE) of materials are based on the action of electromagnetic field over the object to be controlled and the measuring of scattered field which contains information about the shape and dimensions of the examined defect as well as its electromagnetic (EM) properties (dielectric permittivity, electrical conductivity, magnetic permeability). The modern technologies impose at large scale the use of new materials that should be nondestructive tested in order to reach the performances required by design.

For the amagnetic object the Maxwell-Ampere equation can be written as [1]

\[ \nabla \times \vec{H} = \vec{J}_e + \frac{\partial \vec{D}}{\partial t} \]  

(1)

where \( \vec{J}_e \) is the effective electric conduction current, \( \vec{D} \) is the electric flux density and \( \frac{\partial \vec{D}}{\partial t} \) is the effective displacement electric current density. Dielectric permittivity, \( \varepsilon \) of the medium is recognized as being complex, \( \varepsilon = \varepsilon' - j \varepsilon'' \) and in these conditions

\[ \nabla \times \vec{H} = \vec{J}_{tot} = \vec{J}_{ce} + \vec{J}_{de} = (\sigma_s + \omega \varepsilon'') \vec{E} + j \omega \varepsilon' \vec{E} \]  

(2)

\( \vec{J}_{ce} = (\sigma_s + \omega \varepsilon'') \vec{E} \), represents effective electric conduction current density; \( \vec{J}_{de} = j \omega \varepsilon' \vec{E} \), effective displacement electric current density; \( \sigma_s \) is the static field electric conductivity.

For the ferromagnetic or ferrimagnetic object properties to be examined, the Maxwell – Faraday equation can be written

\[ \nabla \times \vec{E} = -\vec{M} - \frac{\partial \vec{B}}{\partial t} \]  

(3)
where \( \vec{M} \) is the impressed (source) magnetic current density, \( \vec{B} \) is the magnetic flux density and \( \frac{\partial \vec{B}}{\partial t} \) is the displacement magnetic current density.

Magnetic permeability \( \mu \) is complex \( \mu = \mu' - j \mu'' \) and in this condition, and can be written as

\[
\nabla \times \vec{E} = -\vec{M} - \vec{M}_c - \vec{M}_d = -\vec{M} - \omega \mu'' \vec{H} - j \omega \mu' \vec{H} \tag{4}
\]

where

\( \vec{M} = \text{the impressed (source) magnetic current density} \)
\( \vec{M}_c = \text{conduction magnetic current density} \)
\( \vec{M}_d = \text{displacement magnetic current} \)

At relatively low frequencies of electromagnetic field, if the object to be controlled is a good electrical conductive (metals, metallic alloys), the displacement electric current can be neglected \( J_{de} \to 0 \) and \( J_{CE} \to \sigma_E \vec{E} \). In this case, there is no clearly limit of frequency but in [2], it is fixed at approximate 10 MHz. At these frequencies, \( \varepsilon'' \to \varepsilon_0 \) and \( \omega \varepsilon'' \to 0 \). Similar phenomena take place in ferromagnetic and ferrimagnetic objects.

The EM methods of NDE using different types of sensors present some advantages, sensitivity to small cracks and other defects, detect surface and near surface defects, inspection can give immediate results, test probes does not need to contact the part, inspect complex shapes and sizes of conductive materials. They have some limitations, only conductive materials can be inspected, surface must be accessible to the probe, skills and training required are more extensive than other techniques, reference standards needed for set-up, depth of penetration is limited, flaws that lie parallel to the probe coils winding and probe scan direction are undetectable.

In case of conductive object type carbon fiber reinforced plastics type (CFRP), where the carbon fibers offer their advantage [3], [4], as long as these are supposed to small mechanical strain under a certain threshold, mechanical fatigue does not appear in the structure, no matter how many cycles are applied to the structure. If the mechanical strains exceed the pre-established threshold that depends by physical-mechanical properties of the structure and the loading type, the phenomenon is felt and the structure requires nondestructive monitoring.

Another electromagnetic structure, extremely studied is conductive strip gratings made from conductive strips that can be metals or metallic alloys, carbon fibers, regions with high concentrations of carbon nanotubes (CNT) or graphene, having \( \varepsilon' < 0 \), separated by dielectric regions with positive dielectric constant. In the same category is corrugate metallic strip grating.

CFRP and a series of parts and appliances as metallic strip gratings that form the core of electronic packages today by providing the ability for inter-chip communication also need to be nondestructively tested [5-8].

For this reason, CFRP, which have especial mechanical properties [3] but can get which delaminations due to low energy impacts [9], metallic strip gratings, which can present interruptions, short circuits, or alignments errors, have required the use of new type of sensors [10]. In both cases, the carbon fibers diameters and the metallic strip width are smaller than the wavelength of the incident radiation. Also, the distance between fibers and respective the slits widths accomplish the same conditions imposing the work at frequencies in the range from hundreds of MHz to GHz [11].

This paper proposes to present the results obtained in NDE of metallic strip gratings and CFRP composite materials that can be considered as multilayered strip gratings structures due to the carbon fiber conductivity. The possibility to manipulate the evanescent waves that
appear in the space between carbon fibers or in slits of metallic strip gratings, using electromagnetic sensor with metamaterial lens allows a spectacular improvement of the spatial resolution, leading to detection of interruption, short circuits of metallic strips in printed circuit boards as well as nonalignment of carbon fibers, lack of resin or voids as well as delamination induced by low energy impacts.

2. Conical Swiss rolls as metamaterials

For the detection of depth cracks with small opening is difficult to apply high frequency EM methods using “classical” sensors because the standard penetration depth is comparable with crack depth. This type of cracks was emphasized using EM sensors with metamaterials lens [9].

The spectacular properties of materials can be obtained by manipulation, not of the atoms and individual molecules, but of certain structures, thus, the composites being created. The metamaterials is an arrangement of artificial structural elements designed to achieve advantageous and unusual properties nowadays, a multitude of metamaterial structural elements types are known, conferring special electromagnetic properties.

The term metamaterials [12], [13] has attracted attention from the scientific community due to their promising applications (perfect lenses, antenna with improved performances, controllable reflection and transmission devices, and electromagnetic absorbers) [14-17].

Because the wavelength of electromagnetic radiation is large (at 300 MHz, the wavelength in air, $\lambda_0=1$ m), the condition that the element should be much smaller than the wavelength is accomplished.

A conical Swiss roll (CSR) consists of a number of spiral wrapped layers of an insulated conductor on a conical mandrel [18]. The extraction of the constitutive parameters of the metamaterials is made by measuring S parameters according to the method presented in [19], and the principle scheme has been presented in [9]. According to [18] the capacitive and the conductive elements of the structures create a resonant LC circuit that the induced currents are subjected to, and therefore a resonant $\mu$ that takes high positive and eventually negative value for a range of frequencies is achieved [20]. Thus, a CSR can act as radiofrequency magnetic flux concentrator [9].

The dependency of frequency for the effective magnetic permeability of CSR having 5 layers, 20 mm large base diameter, 3.2 mm small base diameter, 55 mm the height of truncated cone and 200 the aperture of the top angle is presented in figure 1 [9].

![Figure 1. The frequency dependence of effective permeability of conical Swiss roll](image)
It can be observed that the effective magnetic permeability became high for certain frequency range, whereas for certain frequencies it became negative. As applications in the domain of electromagnetic nondestructive examination we are proposing an optimized work frequency of 72.5 MHz which assures a magnetic effective permeability of 22. The frequency range for which the effective permeability is negative is extremely narrow. The effective permittivity and permeability can be determined by measuring reflection and transmission coefficients for normal incidence of electromagnetic wave to material slab [17] because $S_{11} = R; S_{21} = T \exp(jkd)$ where $R$ and $T$ are reflection, respective transmission coefficients.

Using the Network/Spectrum/Impedance Analyzer, type 4395A Agilent USA, the electromotive force (emf) induced in the detection coil that is displaced with a XY motorized stage Newmark type over the small basis of the CSR at the distance of 1mm has been measured. The dependence of the amplitude of the emf induced in the reception coil at the scanning along the small base of Swiss roll at a lift-off 0.2 mm is presented in figure 2 [9].

![Figure 2](image)

Figure 2 The frequency dependency of the induced emf amplitude in the reception coil at the scanning along the small base of the Swiss roll. Lift-off 0.2mm

It can observed that in the zone corresponding to the diameter of the small base of CSR, for a frequency that assures a maximum of effective magnetic permeability of the radio frequency, magnetic flux is very high. Supplementary on this aperture, the magnetic flux is almost constant, fact that suggests the existence of an electromagnetic plane wave.

3. Metamaterials lens for nondestructive evaluation

Using this type of metamaterial-CSR, a series of a new types of applications such as electromagnetic nondestructive evaluation procedures can be designed. These media have special properties such as negative permittivity and very high or negative permeability in the range of radio frequency and, also, are lossless within a narrow frequency range. These properties are dependent on the selection of structural elements types, geometrical dimensions and the dimensions of unit cell as well as the operation frequency.

3.1. Theoretical development

One of the possible applications of electromagnetic metamaterials sensors for nondestructive evaluation is represented by the metamaterial lens.

Let’s considering a metamaterial slab characterized by effective permittivity $\varepsilon_{\text{eff}}$ and effective magnetic permeability $\mu_{\text{eff}}$. The refractive index of the metamaterial slab is
and the surface impedance is given by

\[ Z = \frac{\mu_{\text{eff}}}{\varepsilon_{\text{eff}}} \]  

The connection between \( \varepsilon \) and \( \mu \) for a medium, as the wave propagation through it could be schematically represented [21] as in figure 3.

According with [12] when \( \varepsilon_{\text{eff}} = -1 \) and \( \mu_{\text{eff}} = -1 \), the refractive index of metamaterial slab is \( n = -1 \), and the surface impedance \( Z = 1 \), so there is no mismatch and consequently no reflection on the interference slab-air. A slab of this material not only focuses the electromagnetic field, but also focuses the evanescent waves.

In the same time, the metamaterials with \( \mu_{\text{eff}} \) large act over electric field as in [22]. Thus an assembly of two CSR can acts as electromagnetic sensors with metamaterials lens. This is an absolute send receiver type, acting over magnetic field at frequency for which \( \mu_{\text{eff}} = -1 \), and over electric field at frequency for which \( \mu_{\text{eff}} \neq +1 \). Such a lens is presented in figure 4.

Let’s consider a conductive strip grating illuminated with a plane electromagnetic wave. In very near field, as shown above, evanescent waves can appear, they could be manipulated using electromagnetic sensors with metamaterials lens. A conductive screen, connected to ground, and having a circular aperture with diameter \( d \) is placed between the object and lens. The distance between the center of the lens and object is \( d_1 \), the image being formed at distance \( d_2 \) from the lens. The circular aperture is defined by pupil function \( P(x,y) \)
\[ P(x, y) = \begin{cases} 1 & x^2 + y^2 \leq d^2 \\ 0 & \text{in rest} \end{cases} \] (7)

The object is \( O(x,y) \) and its image through lens will be \( I(x',y') \) given by [23]

\[
I(x', y') = \frac{1}{\lambda^2 d_1 d_2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp \left[ \frac{jk[(x' - x_i)^2 + (y' - y_i)^2]}{2d_2} \right] P(x, y) \exp \left[ \frac{jk(x_i^2 + y_i^2)}{2f} \right] dx dy dx_i dy_i.
\] (8)

where \( f \) is the focal distance of the lens equal with the height of conical Swiss roll, \( \lambda \) is the wavelength in vacuum and \( k = \frac{2\pi}{\lambda} \) is the wave number.

If the frequency is selected so that the magnetic permeability of lens shall accomplish the condition \( \mu_{\text{eff}} >> +1 \), the electrical evanescent modes can be manipulated, meanwhile, if the frequency is selected so that \( \mu_{\text{eff}} = -1 \), the magnetic evanescent modes can be manipulated.

3.2. Electromagnetic sensor using metamaterial lens

The generation of evanescent waves in very thin cracks of metallic pieces, in carbon fibers of CFRP or in slits of metallic strip gratings of printed circuits is done using the transducer presented in Figure 5.

This type of metamaterials sensor for electromagnetic NDE is an absolute send receiver sensor described in [21]. The two conical Swiss rolls that form the lens assure the passing of evanescent waves with small dumping, which are concentrated on the surface of the reception coil. A relatively uniform angular spectrum can be obtained by scattering an electromagnetic wave on a small scatter of circular shape made from a material considered as perfect electromagnetic conductor (PEC), having an aperture of 0.1mm. That improves the sensor’s spatial resolution, and is placed in the focal object plan of the lens. The diameter of the focal spot of the metamaterial lens is given by [23] and is equal to the diameter of the small base of the CSR (i.e. 3.2mm) according to figure 4.
During the measurement, the transducer is maintained in fixed position and the samples are displaced in the front of the sensor’s aperture, with an automatic XY displacement system, Newmark, with 0.1mm scanning step. The sensor is coupled with a Network/Spectrum/Impedance Analyzer, 4395A Agilent, the real and the imaginary components of the signal induced in the reception coil being measured [23].

4. Studied samples. Experimental results

The performances of the metamaterials sensor for electromagnetic nondestructive evaluation were tested on the conductive strip grating from flexible printed circuits for detection of eventual interruption of the strips or short circuits between traces and on CFRP composite plate with 5H satin woven carbon fibers.

From flexible printed circuits, a region having strip gratings $x_{m}=0.6$ mm, thickness of metallic strip $5$ µm and distance between slits $x_{d}=0.4$ mm is studied, figure 6a. Metallic strip grating being illuminated by a TM$z$ polarized electromagnetic wave, the z axis being orthogonal on the metallic strips plane, only one a single pure evanescent mode is induced in slits at excitation frequency of 500 MHz [23]. This mode can be detected and visualized using metamaterial lens, the parameters of CSR being presented in [24]. It is considered that the wavelength of the incident field is $\lambda=0.6$ m (corresponding to 500 MHz frequency), and the electrical conductivity of silver is $\sigma_{Ag}=6.2873\times10^{7}$ S/m and at frequencies around 500 MHz, the dielectric permittivity of silver is $\varepsilon_{m}=-48.8+i\cdot3.16$ [25]. An interruption of a strip stops the propagation of the evanescent waves in the nearest slit; thus the amplitude of emf. induced in the reception coil practically decreases to zero when the circular aperture of the transducer is over the respective slits. This is presented in figure 6b, which depicts a scan with 0.1 mm step of $20\times20$ mm region from metallic strip grating when one strip is interrupted by a cut with 0.2 mm width.

![Figure 6. The studied sample: a) metallic strip gratings; b) amplitude of the electromotive force induced in the reception coil for interrupted strip](image)

Plates from CFRP composite materials having 6 layers of carbon fibers woven type 5 harness satin (Carbon T300 3K 5HS) with a layout that assures the quasi-isotropic properties are studied. The polymer matrix is made of Polyphenylene Sulphide (PPS). The thickness of the plate is 4.2 mm with 0.5 volume ratio of carbon fibers. The plates are produced by CETEX, Netherlands, figure 7a. On these plates, delaminations due to impact with different energies have been induced using a spherical impactor with 20 mm diameter. In figure 7b is presented the amplitude of the signal delivered by the electromagnetic transducer with metamaterial lens that respects with high fidelity the structure of the first layer of carbon woven 5H type at the scanning of a region of composite which contains a delamination due to an impact with 6J energy. On the edges of the electromagnetic image, the structure of the woven can be
observed; in the central zone, the delaminated region is emphasized. This zone becomes electromagnetically detectable due to the modification of the electrical conductivity on the normal direction to the woven plane as consequence of the impact [6].

Figure 7. The studied samples: a) CFRP composites; b) electromagnetic image through the metamaterial lens

Conclusions

The metamaterials have started to be studied mainly in the last decade, both from theoretical and experimental point of view. Using new type of metamaterial-CSR, a series of new types of applications such as electromagnetic nondestructive evaluation procedures can be designed. These media have special properties such as negative permittivity and very high or negative permeability in the range of radio frequency and, also are lossless within a narrow frequency range. These properties are dependent on the selection of structural elements types, geometrical dimensions and the unit cell’s dimensions, as well as the operation frequency. Currently, these are a wide range of structural elements. These are mainly based in on the fact that the CSR presents high effective magnetic permeability in the range of radio frequencies such that, due their shapes, can serve as radio frequency magnetic flux concentrator. By coupling two CSR, metamaterial lenses can be designed and studied using Fourier optics. The electromagnetic sensors based on metamaterial lenses that allows the manipulation of evanescent waves can reach a spatial resolution of $\lambda/600$ and can be used for NDE of the conductive strip grating from flexible printed circuits for detection of eventual interruption of the strips or short circuits between traces and for the examination of CFRP composites for visualization of carbon fibers layout and delaminations. Clear image of the woven of carbon fibers from CFRP can be obtained and delamination due to impacts with low energies can be emphasized.

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