University “Alexandru Ioan Cuza”
Faculty of Physics

Ph.D. Thesis summary

CONTRIBUTIONS TO THE STUDY OF ELECTROMAGNETIC FIELD INTERACTION WITH MULTILAYERED COMPOSITE MATERIALS. APPLICATIONS TO MICROSENSORS

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Introduction

The thesis with the title *"CONTRIBUTIONS TO THE STUDY OF ELECTROMAGNETIC FIELD INTERACTION WITH MULTILAYERED COMPOSITE MATERIALS. APPLICATIONS TO MICROSENSORS"* should be a study of electromagnetic field interaction with composite materials reinforced with carbon fibers having polymer matrix.

The thesis is structured in six chapters

In the **first chapter** were described the principal physical-mechanical properties of the multilayered composite materials reinforced with carbon fibers and having polymer matrix, as well as the principal types of defects in composite materials and their influence over the physical – mechanical properties. In parallel, electromagnetic methods for evaluation of the carbon fibers reinforced composite materials having polymer matrix have been analyzed and for determination of mechanical properties of multilayered composites.

In the **second chapter,** an analysis of eddy current propagatiob in conductive materials has been carried out.

In the **third chapter**, the composite materials taken into studied and the properties of laminas have been presented.

In **chapter four**, the experimental set-ups used in the development of the thesis were presented

In **chapter five** are presented the contributions to the study of eddy current holography. For electromagnetic nondestructive evaluation of layered materials having the faces from composite reinforced with carbon fiber woven and core from aluminum honeycomb, I have developed a method based on the principle of eddy current holography using a transducer with orthogonal coils.

In **chapter six** are presented the contributions to the high frequency electromagnetic nondestructive evaluation of the composites reinforces with carbon fibers.

With a transducer developed using conical Swiss rolls for generation of a plane electromagnetic wave in the plane of small basis of the con, I have emphasized the structure of the carbon fibers into a composite materials reinforced with carbon fibers 5H satin types, as well as delaminations induced at impact with 2.5J energy.

Using an assembly of two conical Swiss rolls with the large basis front to front I realized a lens with metamaterials of which functioning has been described using the Fourier optics methods. For the realized lens, Point Spread Function has been calculated and measured, the experimental data validating the righteous of the developed theoretical methods.

The conclusions of the analysis of the experimental results are synthetized at the end of the thesis.

CHAPTER III
MATERIALS TAKEN INTO STUDY

III.1 CFRP composites plates

In the frame of the thesis I taken into study composite materials having carbon fibers woven as reinforcement and plastic materials as matrix, *CFRP- Carbon Fiber Reinforced Plastics.*The studied materials are laminated plates, having thickness 1.91±0.1mm, the measurements have been carried out with a micrometer. The matrix of the studied composite materials is made from polyphenilene sulphide PPS.

III.2 Multilayered composite materials having CFRP faces and aluminum alloy honeycomb core

Other type of material studied in the frame of my thesis is multilayered composite with faces from carbon fiber reinforced composite and the core from honeycomb structure from aluminum alloy, named sandwich.

Stratified composites made from two plates of carbon epoxy plates, with 4.2mm thickness, reinforced with 16 layers of prepreg carbon fibers woven, with 0.42 volume ratio, between the two plates, the honeycomb core made from Al 3003 were inserted. The dimensions of one cell are 3.175mm and 15mm height. The structure was glued with epoxy resin, Hexcel 600 type and pressed with 1000N force.

CHAPTER V
CONTRIBUTIONS TO THE STUDY OF EDDY CURRENT HOLOGRAPHY. APPLICATION TO NONDESTRUCTIVE EVALUATION OF LAYERED COMPOSITE MATERIALS

V.1 Principle of eddy current holography

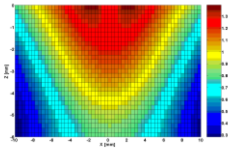
In the examination by electromagnetic procedures, the transducer, respective the equipment delivers a complex signal, the amplitude and phase components or real and imaginary components must be treated independently in the inversion problems.

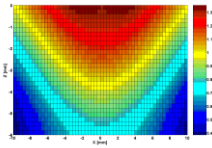
To obtain supplementary information about the shape and location of degradation, the holographic procedure named *Rayleigh-Sommerfeld* is applied, consisting in retropropagation of the recorded hologram in the plane of inhomogeneity.

V.2 Eddy current transducer for holographyc applications

The transducer with orthogonal coils, connected into an impedances bridge has been described in [17,18].

Examining the data from Figure V.6 it can be observed that the wave front of the electric field can be considered spherical for a lift-off of 4mm.


a)


b)

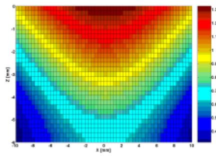
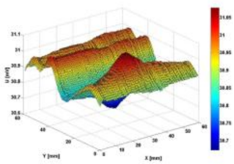

c)

Figure V.6 The results of the simulation of the electric field generated by the emission part of the transducer with orthogonal coils: a) Lift-off: 0.5mm, b) Lift-off: 2mm, c) Lift-off: 4.8mm

V.3 Holography evaluation of composite materials delaminations

In Figures V.7 a and b are presented the information obtained for the amplitude and phase of the signal induced in the reception coils of the transducer at the scanning of 60x60mm area for a CFRP plate that assures the face of the sandwich composite, the plate being impacted with 0.75J energy.


a) amplitude

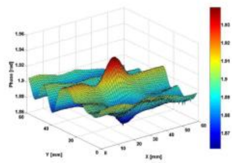

b) phase

Figure V.7 Eddy current signal at the scanning of CFRP plates from the sandwich composite

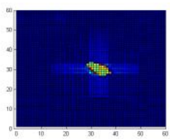


Figure V.8. Holography imagine of delamination due to an impact with 0.75J energy on the composite taken into study

V.4 Evaluation of the defects in the core of the multilayered composite materials using eddy current holography

The region from the multilayered composite that contains the damaged area presented in Figure V.9.a was scanned with 0.1mm step. For comparison, a region with good cells has been scanned [41].


a)

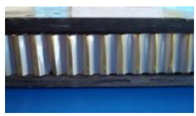

b)

Figure V.9 a) damaged cells on honeycomb core, b) multilayered composite

It can be observed that the cells structure is almost visible in Figure V.10, even over it is the carbon epoxy plate. In Figure V.11 it can be observed that between the good region and damaged region there is difference.

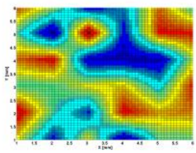


Figure V.10 Holography of a region with good cells

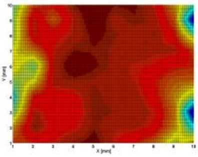


Figure V.11 Holography of a region with deteriorated cells

CHAPTER VI
CONTRIBUTIONS OT HIGH FREQUENCY ELECTROMAGNETIC NONDESTRUCTIVE EVALUATION OF COMPOSITES REINFORCED WITH CARBON FIBERS

VI.1Near field of the emission part of high frequency electromagnetic transducers and its scattering on conductive fibers

VI.1.1*The field scattered by a conductive fiber under the action of a plane electromagnetic wave*

The problem of the electromagnetic field can be reduced, as model, at the calculation of scattered field on a single conductive wire embedded into a dielectric matrix, placed in free space. This problem has been developed in [77] using the algorithm presented in Figure VI.5. To verify the righteous of the algorithm, as well as for obtaining the image of the carbon fibers layout inside the composite material, I have realized a special transducer, emission reception type, absolute, presented in Figure VI.6.

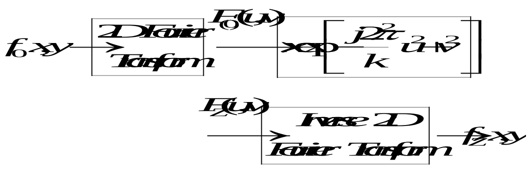


Figure VI.5 Image through aperture given by Fresnel diffraction

Figure VI.6 electromagnetic transducer

Analyzing the results presented in Figure VI.7. a, it can be observed that the layout of the carbon fiber in the composite is impossible to identify. In Figure VI.7.b is presented the same region but scanned with the screen in the front of the transducer. It can be observed that the layout of the carbon fibers woven become visible.

a) without aperture *b) with aperture*

Figure VI.7 Dependency by the position of the real component of electromotive force induced in the reception coil at the scanning of 20x20mm, lift-off 0.2mm, frequency 400MHz

The image in Figure VI.7.b represent in fact the function $f_z(x,y)$, evidently only the real component. In order to obtain the function $f_0(x,y)$ according to the algorithm presented in Figure VI.5, we must effectuate a series of inversion, finally, the results from Figure VI.8 being obtained.

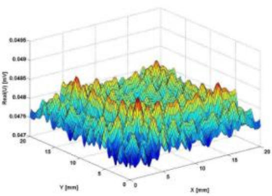
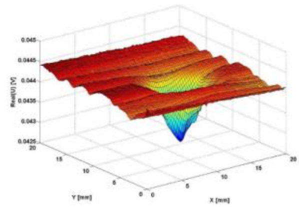


Figure VI.8 Imagine of the surface reconstructed from the image of Fresnel diffraction through a circular aperture



FigureVI.9 Region impacted with 2.5J

The problem was if this problem, that I developed and presented integrally in [77] can be used at the evaluation of delamination due to impact with low energy of the materials taken into study. In these conditions, I scanned a region of the composite that has been impacted with 2.5J energy, the minimum energy at which the delamination could be emphasized using the ultrasound methods presented in Chapter 4, methods considered as standard for detection and evaluation of CFRP.

In Figure VI.9 are presented the results at the scanning of $20x20mm^2$ region that contains a delamination due to an impact with 2.5J energy, after the application of the procedure described above. It can be observed that the delamination is obvious and correctly positioned reported to the results of ultrasound investigation [77].

VI.2 Electromagnetic nondestructive evaluation of composite materials reinforced with carbon fibers woven using metamaterials

From the point of view of metamaterials, an idea very productive was to use a new type of metamaterials, patented by Nondestructive Testing Laboratory, NIRDTP [101,115-117], namely conical Swiss rolls, the metamaterials Swiss roll type but by cylindrical shape being introduced by Professor Pendry [109-113].

VI.2.1 Conical Swiss roll as metamaterials

VI.2.1.1 Realization of conical Swiss roll

A conical Swiss roll consists in a number of insulated conductive materials wounded on a conical mandrel. The insulated conductor is made from a layer of Copper with 18µm thickness and a polyamide layer having thickness 12µm, high frequency.

VI.2.1.2. Experimental determination of the constitutive parameters of conical Swiss roll

To determine the effective magnetic permeability of a Swiss roll, the S parameters have been measured using Network/Spectrum/Impedance Analyzer 4395A Agilent coupled with S Parameter Test Kit 87511A, Agilent, USA.

The electromagnetic field is generated by a coil with two turns having 16mm diameter, made from Cu wire, 1mm diameter. The response given by the conical Swiss roll from metamaterials is detected with a reception coil having 2 turns with 3mm diameter, figure VI.11

It can be observed that the magnetic effective permeability became high for a known frequency interval, and for other became negative, Figure VI.14. As application in electromagnetic nondestructive evaluation I proposed an optimal work frequency of 72.5MHz that assures a value of effective magnetic permeability of 22. At the frequency at which the relative effective magnetic permeability is maxim, the conical Swiss roll acts like an alternative magnetic flux concentrator. This properties was observed experimentally and it was presented in [101].

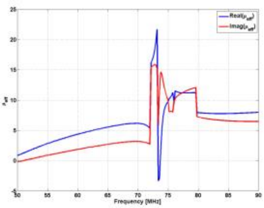


Figure VI.14 Dependency by frequency of the effective magnetic permeability of conical Swiss roll

VI.2.1.3. Conical Swiss roll acting as concentrator of alternative magnetic flux

The electromotive force induced in reception coils was measured when the reception coil is displaced by a XY motorized system over the small base of conical Swiss roll using the Network/Spectrum/Impedance Analyzer 4395A.

It can be observed that in the region corresponding to the small base of the truncate cone, for a frequency that assures maximum effective magnetic permeability, the magnetic flux concentration is high.

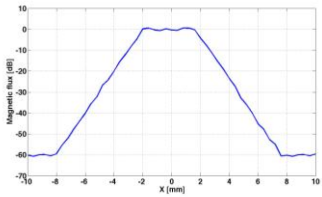
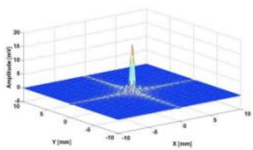


Figure VI.15 Dependency by frequency of the electromotive force induced in reception coil at a scanning along the small base of the Swiss roll. Lift-off 0.2mm

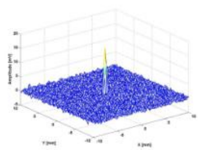
VI.2.1.4 Images in near field using conical Swiss rolls as electromagnetic lens

Considering two conical Swiss roll, with the two large bases front to front. Due to the magnetic flux concentrator properties, the two Swiss rolls create a lens. The object is placed in the plane of the small base of the first Swiss roll, the image being obtained in the focal plane of the lens, localized in the plane of small base of the second Swiss roll.

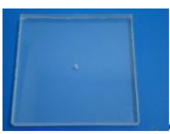
As scatter, I used a Cu cylinder, 1mm diameter, embedded in a Plexiglas plate (Figure VI.17c). The experimental measurements were carried out with Network/Spectrum/Impedance Analyzer 4395A Agilent with the lens in fixed position ad t the plate with the cylinder displaced with XY motorized system, Newmark type, the scanning step was 0.25mm in both directions. The operating frequency was 72.5MHz, corresponding to the region where the magnetic permeability of the conical Swiss roll is maxim.



a)



b)



c)

Figure VI.17: a) The filed calculated in the focal plane for a circular section with small dimensions, b) The field calculated in the focal plane for a cylinder with 1mm diameter, c) the scatter

Analyzing the data presented above it is clearly seen that the realization of lens from metamaterials in the domain of radiofrequency using conical Swiss roll is possible, the perturbations are minim and their calculation can be made on the basis of Fourier optics. For obtaining high resolution electromagnetic images, the surface of the scatter must have small roughness.

V.2.2. Electromagnetic nondestructive examination of composite plates using transducers with metamaterials

The optimal conditions for functioning of the transducer with metamaterials using conical Swiss rolls were established from the measurements of the network parameters. The transducer has been used for the effective visualization of delamination of carbon fibers reinforced plastic due to impact.

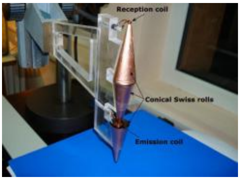
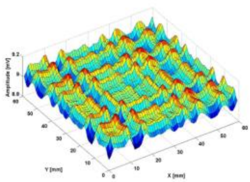
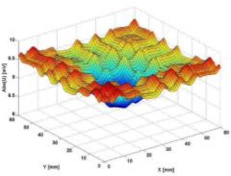


Figure VI.18 The electromagnetic transducer using metamaterials lens

The structure of CFRP obtained with this transducer respects with precision the image of the first layer of carbon fibers woven 5H satin. In Figure VI.20 is presented the signal delivered by the transducer at the scanning of a region of composite containing a delamination due to an impact with 2.5J energy. On the electromagnetic image it can be seen on the sides the structure of the woven and in the center is emphasized the delamination. This region became detectable due to the modification of local electrical conductivity in the direction normal to the woven due to the impact.





Amplitude of the signal delivered by the transducer at the scanning of CFRP
Figure VI.19 an intact region ***Figure VI.20 with delamination due to impact***

For the range of frequencies between tens and hundreds of MHz, the concentration of the incident electromagnetic field can be obtained using a new type of Swiss roll, the conical one, made from metamaterials. The evanescent waves that appear at the surface of the scatter can be concentrated using metamaterials lens made from two conical Swiss rolls. This method gave good results at the examination of CFRP plates, emphasizing the delamination due to low energy impacts. The proposed method is limited because the evanescent waves are damped on small distances in common environment due to roughness that affects the quality of the electromagnetic images.

Conclusions

- In the frame of my thesis I have studied the interaction of electromagnetic field with the composite materials reinforced with carbon fibers, having polymer matrix.
- I have studied plates of composite materials having the reinforcement from successive layers of carbon fibers, disposed along the same direction, having 6 layers and 1.91mm thickness. I also studied materials with reinforcement from carbon fibers woven, 5H satin type with biaxial anisotropy. In both cases the matrix was poly phenilene sulphide (PPS), the materials being produced by TenCate Netherlands, the principal producer of composites for the aeronautic industry. I studied also the composite materials from the honeycomb core stratified composites having 4.2mm thickness.
- I contributed to the development of the transducer with orthogonal coils, at the development of the measurement system based on Network/Spectrum/Impedance Analyzer and XY motorized displacement system, the equipment being coupled with PC through IEEE 488.2 and RS 232 interfaces. The programming of the displacement as well as the data acquisition is carried out by command software developed in Matlab. I developed a numerical code for the effectuation of operations specific to eddy current holography. I emphasized regions where are adhesive lack between the faces and core with surface smaller than $100mm^2$.
- Treating the problem in Fourier optics, following a scheme dedicated to Fresnel diffraction, the layout of the composite fibers became visible, succeeding to also emphasize delaminations.
- I observed that in order to have a good detection sensitivity, allowing emphasizing the structure of carbon fibers, the working frequency must be in the range of hundreds of MHz.
- I have participated at the realization of a new type of metamaterials, namely conical Swiss roll, made from layers of Cu and polyamide laminated without adhesive and from which circular shapes have been cropped in order to roll them on a conical mandrel. I have shown that this metamaterials can present, for a certain range of frequency, a relative magnetic permeability of 22, the materials that form the foil being both paramagnetic.
- Conical Swiss roll presents the properties of alternative magnetic field concentration. I show that, if at the small basis of conical Swiss roll the magnitude is considered 0dB, at 6mm from the center of the small base, the amplitude decrease with-40dB, meaning 100 times. At the same distance between the emission and reception coils, at 55mm, the amplitude of electromagnetic fields is 1000 times smaller when the measurements are done in air that when the measurement is made in the center of small base of the conical Swiss roll.
- Using an assembly of two conical Swiss rolls, with the large bases front to front, I have realized a metamaterials lens, its functioning being described with Fourier optics.
- With the transducer developed using conical Swiss roll for the generation of

plane electromagnetic waves in the plane of the small base of the metamaterials and a metamaterials lens, with a reception coil placed in its focal point I succeed to emphasize the layout of carbon fibers woven in carbon fiber reinforced composites with carbon fibers type harness Satin H5-T300JB, as well as delaminations induced by impacts with 2,5J energy

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