Nondestructive testing sensor using semiregular architecture with folding ligaments

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Abstract. In present, much more studies on patterned structures composed of periodic unit-structures have been performed. These studies mainly based on the electromagnetic wave propagation, because the variation of physical properties of the patterned structure depends on the change in the unit-structure. Structural topology optimization has made remarkable progress over the past decades. The periodic topology of many periodic cellular makes the analysis of their wave propagation characteristics particularly interesting. This paper presents the results obtained at the electromagnetic testing using a structure in a semiregular arrangement with “exotic” behavior. The CAD/CAM models of reconfigurable folding architecture were designed in the multiple flat unit cells structure considering that the kinematics of a structure with ligaments is function of the angle in the XY horizontal plane. It was followed in response to the modification of the architecture and the size of the structure, their response to the interaction with the electromagnetic field. The simulation of the operation of the wavelength excitation process, first realized theoretically using the Finite Difference Time Domain (FDTD) method, was performed using specialized XFDTD software.

1. Introduction
Antenna arrays, frequency selective surfaces, reconfigurable antennas, and other radio-frequency (RF) devices has been developed [1], because they have advantages over standard devices, such as band-switching and frequency tuning [2, 3], beam-steering [4], polarization adjustment [5], and many other capabilities which are needed in future wireless communication systems.

Semiregular architecture with electromagnetic sensors with metamaterial is used to make complex microstructures by micro-assembly and to create 3D structures. These are obtained from subsets of rigid parallelepiped faces with ligaments at the tips leading to totally special, foldable geometries with special properties, falling into the MMs category [6]. It is important to maintain the material properties after making changes to the structure. A property of material used in creating geometric patterns and studying dimensional change in folding structures is the Poisson coefficient defined as the negative ratio of elastic tension in the normal direction to applied load. At the time of stretching, Poisson negative coefficients expand in the direction perpendicular to the applied load. Based on the elasticity theory, the Poisson coefficient for a linear isotropic elastic material is limited [7]. Contrary to isotropic solids, Poisson coefficient value for elastic anisotropic materials is not limited. The folding structures are anisotropic, with deformation taking place due to folding and depression. Thus, in folding
structures, (in most of the architecture geometry parameters) the Poisson coefficient can exceed the limit of isotropic materials [8].

Also, the reconfigurable antennas are designed by directly changing the antenna geometry using mechanisms. In [9], a tunable helical antenna is presented, which uses a shape memory alloy placed in parallel with the antenna to control the antenna height. However, such antennas exhibit geometrical distortion when they are stretched or collapsed and they cannot be efficiently compacted. A tape spring antenna, which can work in both deployable and stowed states, was proposed in [10]. This antenna deploys along a tape line and, therefore, it can only be designed as a dipole or a monopole antenna. In [11], a monopole antenna transforms to a patch antenna with a light-activated hinge, but such hinges cannot guarantee continuity of the antenna element. A foldable array structure for energy harvesting was successfully launched and deployed based on a design, which could be folded rigidly without any of the quadrilaterals in the crease pattern [12]. Concepts of thin shell structures and pantographs have been used as basis for the development of conical log-spiral antennas [13]. A foldable frequency selective surface was also introduced in [14], which comprises of periodic elements arranged on a dielectric sheet. By folding and unfolding the FSS, the resonance frequency shifts.

In non-invasive evaluation of materials, an electromagnetic (EM) wave is generated and directed to the interrogated structure and detected after it has propagated into the structure. Propagation is affected by material properties (density, attenuation, propagation speed); environmental conditions (mechanical loading, border conditions, residual stress, dislocations); measurement conditions (sensor location and size, sensitivity, interrogation frequency, control electronics). The difficulty is to get as much information as possible from a single exam. This information is difficult to decipher. Such a method is pattern recognition. Determining the state of a sample by non-destructive examination using pattern recognition consists of three basic steps: generating and processing data, selecting data inspected and determining the state of the sample from the selected characteristics.

2. Semiregular architecture sensor; theoretical principles and construction

Starting from the concept of flexible semi-rigid structure for the study of the mechanical properties of materials, using the architecture described in [15] the question arises whether this structure could be used in the construction of an electromagnetic sensor [16] for the non-destructive evaluation of materials.

The kinematics of semiregular architecture is a function of the angle in the \(xy\) horizontal plane. The constraints apply to simulate similar conditions in architecture and create the planar freedom degree (GDL) mechanism. Thus, in order to remove rigid movements associated with GDL translation and rotation, all GDL translation points are constrained, and it is assumed that the edges AB and BC of the facet move in the \(xy\) plane and the projection of the length AD remains along the \(x\)-axis. A facet has only one planar GDL. Defines the geometry of the face in equation (1):

\[
l = a \frac{\cos \alpha}{\cos \phi} \quad \text{and} \quad w = 2b \sin \phi
\]  

(1)

where \(l\) is the projected length of the edge \(a\) in the \(xy\) plane in the \(x\) direction; \(w\) is the width of the structure folded into the \(xy\) plane along the \(y\) direction, \(\alpha\) and \(\phi\) angles defined in figure 1. The Poisson coefficient in the plan for this system is given by equation (2):

\[
\nu_{wl} = -\frac{\epsilon_{l}}{\epsilon_{w}} = -\frac{dl/l}{dw/w} = -\tan^2 \phi
\]  

(2)

It is demonstrated that cinematic depends only on the angle \(\phi\). In a UC containing two V- shaped faces, the length \(b\) to the \(a/n\) of the other V shape is scaled while retaining the folding and flaking capability. The unit cells (UCs) with two V forms with the same angle \(\phi\) is creating. For \(n = 2\), the UC
has a planar mechanism so constraints lead to an ideal GDL. This fulfills the conditions for obtaining the kinematic form V.

![Figure 1. Single unit cell of a semiregular architecture.](image)

Thus, the Poisson coefficient in the obtained plan, considering the projected lengths of the folding cells, provides the information that those components that have identical $\nu_f$ can be connected to obtain free-folding and deforming structures having MMs features. For structures made from the V-shapes with the same CU, the Poisson coefficient is given by equation (3):

$$
V_{w_f} = -\frac{\varepsilon_{w_f}}{\varepsilon_w} = -\tan \phi \frac{2nm_1}{m_1(n-1)+1} \frac{a\cos\alpha - \cos^2\phi}{b\cos\alpha + \cos^2\phi}
$$

(3)

for $n = 2$ (note that for $n = 1$ we have $\nu_f$). A single UC has been taken into consideration, thus, $m_1 = 1$ and $n = 2$. Figure 2 presents the Poisson coefficients calculated for different $\alpha$ angles following equation (3).

![Figure 2. Poisson coefficient calculated: (a) on the basis of kinematics; (b) on the basis of length.](image)
3. Simulation and results
To modeling the sensors, we have started from the UC analysis as a whole, taking into account the semiregular architecture. The presence of the metamaterial aims at focusing the field, taking into account the technical aspects related to the use of the intelligent sensor with metamaterials, namely the masking, the selection of materials (their behavior was simulated taking into account the existing tensions and the expansion that may occur). Functional modeling was performed using the Green dyadic function and volume integration method [17] for a UC having rectangular shapes. The current source that creates the field has a complex structure due to the geometry presented in figure 1. As such, we can assume that a Hertz dipole placed at a distance equal to the focal distance of the sensor will generate for longer distances than the focal distance, the same type of field, so a spherical wave front.

In order to validate the semiregular architecture model, the behavior of the structure has been simulated in a FDTD software. For this reason, a development in 256x256 spatial harmonics was used. It is observed that the presence of the UC in front of the source, excitation being electromagnetic wave, at the frequency of 492MHz, without being subjected to mechanical stretching, has the ability to focus the field after crossing it. After stretching with 50% strain, the ability to focus of the architecture is observed also (figure 3) without modification of the parameters. In figure 3 (a) and (b) are presented the responses of a UC excited with an EM wave at the 492MHz frequency.

![Figure 3](image)

**Figure 3.** UC architecture and simulation results: a) UC no deformed; b) UC deformed.

S parameters of the structures were determined using the S-parameter kit of Network/Spectrum/Impedance Analyser Agilent. 4395A on 12-bit quantization. The method of approaching a two-port network provides sufficient facilities for calculating the S parameters, the equivalent scheme is seen as a quadrupole [18].

![Figure 4](image)

**Figure 4.** Experimental measurements of semiregular architecture.

The proposed adoption method is that of a two-port network with transmission and reception coils that are not identical to eliminate the frequency distribution and to obtain a uniform power for the wireless power transfer system. The transfer coefficient of the system is uniform, without regard to the transfer distance in the working range. Parameters S have the advantage of a relatively simple measurement relative to other parameters that characterize the quadrupole, having a particular physical relevance when performing these types of measurements.
Note that $S_{11}$ is related to the reflection coefficient ($\Gamma$), equation (4), while $S_{21}$ is proportional to the transmission coefficient ($T$).

\[
\Gamma = k \pm (k^2 - 1)^{1/2}; \quad k = \frac{(S_{11}^2 - S_{21}^2) + 1}{2S_{11}} \quad \text{and} \quad T = \frac{(S_{11} + S_{21}) - \Gamma}{1 - (S_{11} + S_{21})\Gamma}
\] (4)

Considering that the incident wave is a flat wave and that MM has a thickness $d$, the S parameters can be written as [18, 19] in equations (5-7):

\[
S_{11} = \frac{R_{01}(1 - e^{j2nk_d})}{1 - R_{01}^2 e^{j2nk_d}}
\] (5)

\[
S_{21} = \frac{(1 - R_{01}^2)e^{jnk_d}}{1 - R_{01}^2 e^{j2hk_d}}
\] (6)

where:

\[
R_{01} = \frac{Z - 1}{Z + 1}
\] (7)

$Z$ represent the circuit impedance that can be written in equation (8):

\[
Z = \pm \sqrt{(1 + S_{11})^2 - S_{21}^2} \sqrt{(1 - S_{11})^2 - S_{21}^2}
\] (8)

It follows that by measuring the S parameters the dielectric permittivity of the semiregular architecture as well as the magnetic permeability of an electric circuit which does not contain any component made of ferromagnetic materials might be determined.

4. Conclusions
It has been shown that in 1D semiregular architecture, evanescence waves can occur in the zones between the unit cells constituents (voids) when the structure is excited with discrete sinusoidal electromagnetic wave. Two different values were obtained for the Poisson coefficient in the plan, the kinematics of the semiregular architecture and the length of the integral architecture made from multiple unit cells. Using a numerical code based on the Green dyadic function method and the FDTD volume integration, the semiregular architecture behaviour was simulated demonstrating the capability...
to focus the electromagnetic field response of materials involved in non-destructive testing.

Further research will imply the use of multiple UC on a flexible support in order to investigate complex cylindrical phantoms.

5. References

[1] Gregory MD and Werner DH 2015 Application of the memristor in reconfigurable electromagnetic devices *IEEE Antenn Propag M* 57(1) 239-248

[2] Peroulis D, Sarabandi K and Katehi LP 2005 Design of reconfigurable slot antennas *IEEE T Antenn Propag* 53(2) 645-654

[3] Rajagopalan H, Kovitz JM and Rahmat-Samii Y 2014 MEMS reconfigurable optimized E-shaped patch antenna design for cognitive radio *IEEE T Antenn Propag* 62(3) 1056-1064

[4] Zohur A, Mopidevi H, Rodrigo D, Unlu M, Jofre L and Cetiner BA 2013 RF MEMS reconfigurable two-band antenna *IEEE Antenn Wirel Pr* 12 72-75

[5] Yang F and Rahmat-Samii Y 2002 A reconfigurable patch antenna using switchable slots for circular polarization diversity *IEEE Microw Wirel Co* 12(3) 96-98

[6] Wei ZY, Guo ZV, Dudte L, Liang HY and Mahadevan L 2013 Geometric mechanics of periodic pleated origami *Phys Rev Lett* 110(21) 215501

[7] Ting T C and Chen T 2005 Poisson's ratio for anisotropic elastic materials can have no bounds *Q J Mech Appl Math* 58(1) 73-82

[8] Alaeian H and Dionne JA 2014 Non-Hermitian nanophotonic and plasmonic waveguides *Phys Rev B* 89(7) 075136

[9] Mazlouman SJ, Mahanfar A, Menon C and Vaughan RG 2011 Reconfigurable axial-mode helix antennas using shape memory alloys *IEEE T Antenn Propag* 59(4) 1070-1077

[10] Costantine J, Tawk Y, Christodoulou CG, Banik J and Lane S 2012 CubeSat deployable antenna using bistable composite tape-springs *IEEE Antenn Wirel Propag Lett* 11 285-288

[11] Hayes GJ, Liu Y, Genzer J, Lazzi G and Dickey MD 2014 Self-folding origami microstrip antennas. *IEEE T Antenn Propag* 62(10) 5416-5419

[12] Miura K 1994 Map Fold a La Miura Style. Its Physical Characteristics and Application to the Space Science Research of Pattern Formation, KTK Scientific Publishers 77–90

[13] Olson G, Pellegrino S, Costantine J and Banik J 2012 Structural architectures for a deployable wideband UHF antenna In3rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA p 1836

[14] Fuchi K, Tang J, Crowghey B, Diaz AR, Rothwell EJ and Ouedraogo RO 2012 Origami tunable frequency selective surfaces *IEEE Antenn Wirel Propag Lett* 11 473-475

[15] Bertoldi K, Vitelli V, Christensen J and van Hecke M 2017 Flexible mechanical metamaterials. *Nat Rev Mater* 2(11) p.1066

[16] Grimberg R, Tian GY, Savin A, Steigmann R and Dobrescu GS 2014 Electromagnetic metamaterial sensors for structural health monitoring *Stud Appl Electromag* (XVII) 39 3-10

[17] Grimberg R and Tian GY 2012 High-frequency electromagnetic non-destructive evaluation for high spatial resolution, using metamaterials *Proc Royal Soc A* 30 468(2146) 3080-3099

[18] Savin A, Steigmann R, Bruma A and Sturm R 2015 An electromagnetic sensor with a metamaterial lens for nondestructive evaluation of composite materials *Sensors* 15(7) 15903-15920

[19] Smith DR, Vier DC, Koschny T and Soukoulis CM 2005 Electromagnetic parameter retrieval from inhomogeneous metamaterials *Phys Rev E* 71(3) 036617

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