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EVALUATION OF STRESS IN STEEL STRUCTURES USING ELECTROMAGNETIC METHODS BASED ON UTILIZATION OF MICROSTRIP ANTENNA SENSOR AND MONITORING OF AC MAGNETIZATION PROCESS

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Abstract. In this paper the results of utilization of electromagnetic methods operating in low and high frequency range for evaluation of stress state and plastic deformation in steel elements are presented. In low frequency range Barkhausen noise and magnetic hysteresis loop method for evaluation of stress level and growth of plastic deformation changes were utilized. The methods allow to monitor parameters related to magnetization process under AC field. Additionally in this paper the possibility of utilization of high frequency method for estimation of deformation extent (i.e. elongation) caused by stress will be presented. In this experiment the frequency response (the reflection coefficient S_{11}) is measured. The strong relation of antennas resonant frequency to patch dimensions is utilized in order to obtain information about deformation of the sample

Keyword: nondestructive testing, stress measurement, sensor, ac magnetization, Barkhausen noise, microstrip antenna

OCENA NAPRĘŻEŃ W KONSTRUKCJACH STALOWYCH ZA POMOCĄ METOD ELEKTROMAGNETYCZNYCH WYKORZYSTUJĄCYCH CZUJNIKI MIKROPASKOWE I UMOŻLIWIAJĄCE MONITOROWANIE PROCESU MAGNETYZACJI AC

Streszczenie. W artykule zostały przedstawione wyniki jakie uzyskano za pomocą metod elektromagnetycznych, zarówno niskoczęstotliwościowych, jak i wysokoczęstotliwościowych do oceny zmian stanu naprężeń oraz deformacji plastycznych w elementach stalowych. W zakresie niskich częstotliwości do oceny stopnia naprężenia oraz zmian plastycznych wykorzystano metodę obserwacji szumu Barkhausena oraz magnetycznej pętli histerezy. Metody te umożliwiają monitorowanie parametrów związanych z procesem magnesowania stali polem zmiennym. Dodatkowo w pracy przedstawiono możliwość wykorzystania metody wysokoczęstotliwościowej do oszacowania odkształcenia (w tym przypadku wydłużenia) spowodowanego naprężeniem. W tym celu zaprojektowano i wykonano przetwornik mikropaskowy. W badaniu mierzono odpowiedź częstotliwościową (współczynnik odbicia S_{11}). Silna zależność częstotliwości rezonansowej przetwornika mikropaskowego od wymiarów promiennika została wykorzystana do określenia deformacji próbki

Słowa kluczowe: badania nieniszczące, pomiar naprężeń, czujnik, obserwacja procesu magnetyzacji polem AC szum Barkhausena, antena mikropaskowa

Introduction

Steel is one of the most important material in the development of various constructions. Due to its good mechanical properties and relatively low price, it is used in machinery, shipbuilding, railway, construction, mining and other industries. However during operation time its mechanical properties degrade due to i.e. varying in time environmental conditions (i.e. load corrosion or temperature). Therefore, in the most important parts of the construction, one should examine periodically or monitor the changes of structure properties.

The aim of this paper is to study the possibility of utilization of high frequency method for evaluation of stress in steel. In this case an applied strain changes the dimensions of the microstrip patch antenna sensor fixed on materials surface, resulting in the change of its electrical length and frequency domain parameters [1–3, 12–14].

Furthermore, it is well known that microstructural changes of steel caused by i.e. stress influence the magnetic properties of material [4, 5, 8, 11]. Therefore by monitoring changes of parameters combined with dynamics of AC magnetization (ACM) process of steel it is possible to evaluate the state of the material's structure [6, 11]. Additionally, when material is being magnetized, ferromagnetic structure is changing step by step while rotation of magnetic domains. The stepwise change of the magnetization level can be observed by coil placed in the neighborhood of the material. As a result, a voltage called the Barkhausen Noise (BN) is induced in coil. Introduction of stress into a material results in changes of magnetic properties and in consequence influences size and shape of magnetic hysteresis loop and characteristics of Barkhausen noise signal [4, 6, 7, 10].

In this paper two different sensors for possible application to structural health monitoring systems will be presented.

1. Experiment setup

The utilized methods operating in different frequency ranges were validated in an experiment, in which measurements were conducted for a beam sample made of St3S steel loaded using different force value in order to introduce different strain level.

The sample was attached to the static holding element and the other side was loaded with different weights. The sample was made from St3s steel which parameters are presented in table 1. The scheme of experiment and dimension of the sample is presented in Figure 1. Both sensing devices were placed in the same distance from loading force side by side in order to obtain the same strain level. Distance from the beginning of the sample into the centre of the sensors equals 50 mm.

Table 1. Mechanical properties of St3s steel according to PN-88 H-84020

St3s steel parameters	
Young's modulus E	200 GPa
Yield point	235 MPa
Limit state	380 MPa
Bending Limit state	145 MPa

Measuring system has two subsystems: high and low frequency. The block scheme of proposed system is shown in Figure 2. Photo of measuring system is shown in Figure 3.

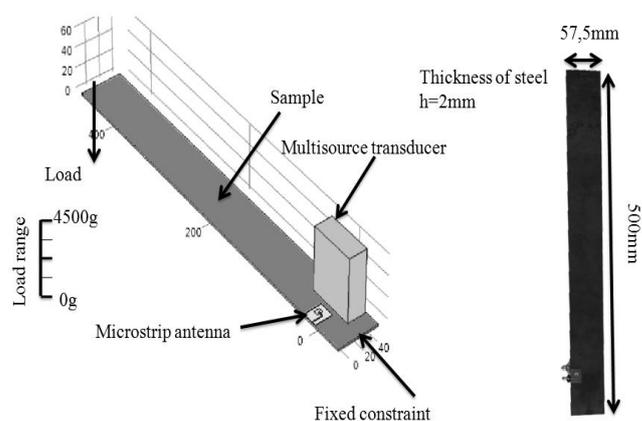


Fig. 1. Scheme of experiment setup and photo of St3s steel specimen with fixed patch sensors

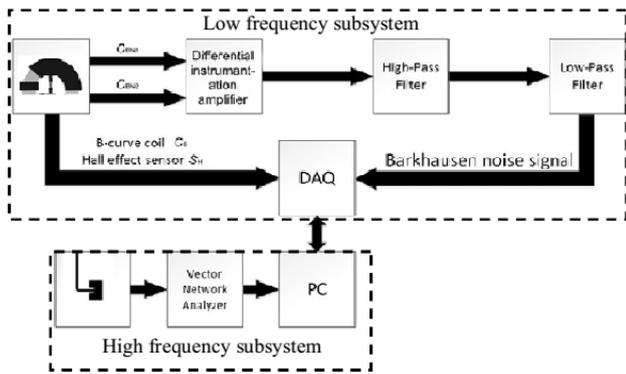


Fig. 2. Block scheme of monitoring system

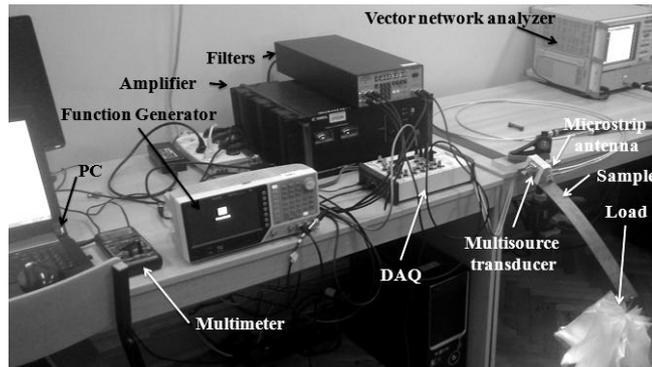


Fig. 3. Photo of measuring system

1.1. High frequency monitoring subsystem

High frequency (microwave) monitoring subsystem consists of microstrip antenna sensor and microwave vector network analyzer to measure the reflection coefficient S_{11} . Antenna sensor was designed for operation frequency of 12 GHz using the following formulas [1]:

- width W of the patch:

$$W = \frac{c}{2 \cdot f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

- the effective dielectric constant ϵ_{reff} of the patch:

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \cdot \frac{h}{W} \right] \quad (2)$$

- the extended incremental length ΔL of the patch:

$$\Delta L = h \cdot 0,412 \cdot \frac{(\epsilon_{\text{reff}} + 0,3) \cdot \left(\frac{W}{h} + 0,264\right)}{(\epsilon_{\text{reff}} - 0,258) \cdot \left(\frac{W}{h} + 0,8\right)} \quad (3)$$

- the actual length L of the patch:

$$L = \frac{\lambda}{2} - 2 \cdot \Delta L \quad (4)$$

- the inset feed point distance y_0 :

$$y_0 = \frac{L}{\pi} \cdot \arcsin \left(\sqrt{\frac{Z_0}{R_{in}}} \right) \quad (5)$$

where:

c – speed of light in free space, f_r – resonant frequency, ϵ_r – relative permittivity of substrate ($\epsilon_r = 4.5$), h – height of substrate, Z_0 – designed impedance of the patch, R_{in} – input resistance for the inset feed.

The antenna sensor produced by the photolithography process. Manufactured antenna and its dimensions are presented in Figure 4. Antenna sensor has been made on the bilateral FR4 laminate thickness 0.5 mm. The patch, microstrip line and ground are made of copper (layer thickness of 35 μm).

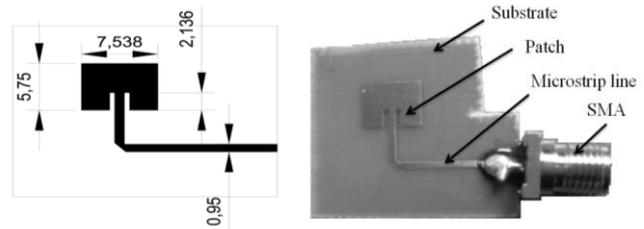


Fig. 4. Photo and dimensions of the patch sensors

The microstrip antenna is fixed using adhesive on the top of sample as shown in Figure 1. The adhesive connection enables transmission of sample deformation to microstrip sensor.

Measurements were carried out using Rohde&Schwarz ZVB20 vector network analyzer in 10 MHz–20 GHz frequency range with step of 2 MHz.

1.2. Low frequency monitoring subsystem

The second subsystem consists of a multi-sensor transducer. The 2D view with dimensions and photo of transducers with depicted description of the elements are shown in Figure 5. This setup allows to observe multiple features set derived from both ACM and BN signals simultaneously. Signals related to tangential component of magnetic field strength H and magnetic induction B were sensed by a Hall effect sensor (S_H) and a pick-up B coil (C_B) respectively. The Barkhausen noise signal U_{BN} is received by unit of two BN coils (C_{BN1} and C_{BN2}) connected differentially placed in middle of transducer. The first coil is fixed closed to the material while the second one is attached in some distance. The differential signal of both coils allows to reduce the level of unwanted environmental inferences. The electrical parameters of transducers' coils are shown in Table 2.

The magnetizing field was generated by excitation coil (C_E) wound on the C-shaped ferrite core and driven with 20 Hz sinusoidal current having RMS value equal to 0.5 A. The excitation waveform was generated by Hantek function generator and then amplified by Fonica WS 702 power amplifier. For pre-processing of the U_{BN} signal the Krohn-Hite 3988 dual channel programmable active filter was used. At the first stage, the differential signal from both BN coils was high-pass filtered and amplified using respectively cut-off frequency of 1 kHz and gain of 50 dB. Next, the low-pass filter was utilized with the cut-off frequency set to 60 kHz and gain to 50 dB. Finally, the U_{BN} signal as well as U_B (sensed by C_B) and U_H (sensed by S_H sensor) ones were acquired by NI USB-6241 BNC DAQ. All procedures were controlled and managed by NI LabView based software.

Table 2. Electric parameters of coils

Coil	C_E	C_B	C_{BN1}	C_{BN2}
L	4.117 mH	1.053 mH	1.576 mH	1.635 mH
Q	6.07	0.576	1.06	1.08
R	163.1 Ω	15.42 Ω	20.03 Ω	20.77 Ω

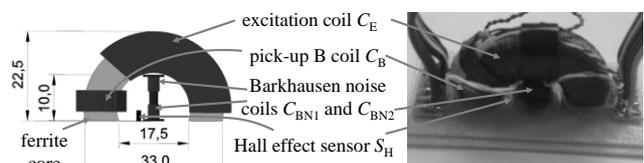


Fig. 5. Block scheme of AC magnetization monitoring system

2. Results of experiments

2.1. High frequency method

In order to evaluate the proposed sensor FEM (Finite Element Method) numerical model was developed in Comsol Multiphysics environment. Both, radio frequency and mechanical modules were utilized according to the following equations:

$$\nabla \times \mu_r^{-1} (\nabla \times \vec{E}) - k_0^2 \left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0} \right) \vec{E} = 0 \quad (6)$$

$$0 = \nabla \cdot \vec{S} + \vec{F}_v \quad (7)$$

where:

μ_r – relative permeability,

\vec{E} – electric field,

k_0 – wave number,

ϵ_r – relative permittivity,

σ – electric conductivity,

ω – angular frequency,

ϵ_0 – dielectric constant,

S – stress tensor,

\vec{F}_v – load defined as force per unit volume.

Mechanical module was utilised in order to obtain deformation of sensors geometry. Subsequently, the RF module enabled calculation of deformed sensor frequency response.

The numerical model with mechanical scheme and calculated total displacement for maximum force (within elastic range of the material stress-strain relationship) are presented in Figure 6. The sample is affected by the force of gravity and the force attached to its end. Mesh consists of 232 265 tetrahedral elements, 25 553 triangular elements, 1496 edge elements, 57 vertex elements. The measurement was carried out in 4–20 GHz frequency range with step of 1 MHz. This step ensured sufficient accuracy.

The reflection coefficient S_{11} represents the power reflected from the antenna related to the incident one. This coefficient is measured in frequency domain. The resonant frequency is the frequency, in which the S_{11} has a local minimum. The reflection coefficient of designed antenna sensor is presented in Figure 7. The electric field distribution for resonant frequency is illustrated in Figure 8.

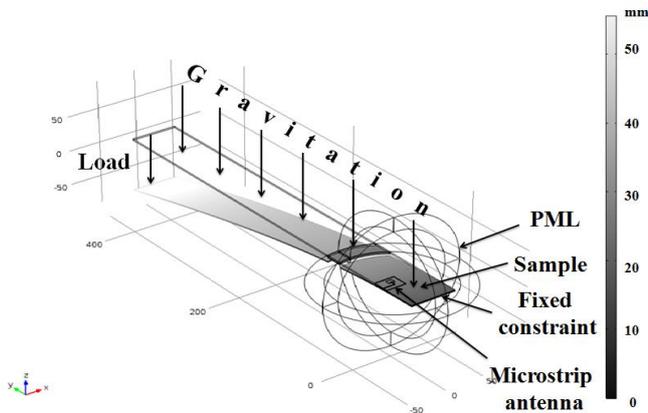


Fig. 6. FEM numerical model of experimental setup with calculated total displacement (gray level)

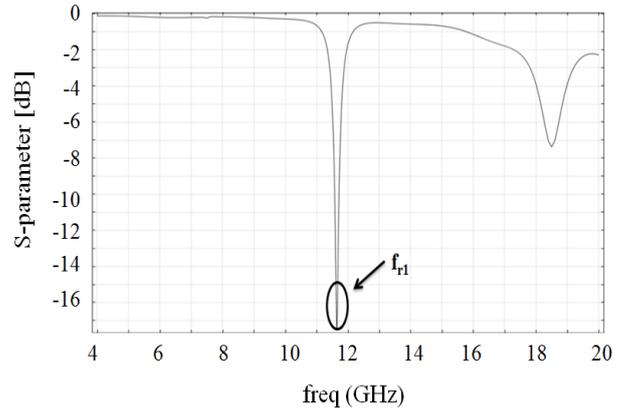


Fig. 7. S_{11} parameter vs frequency

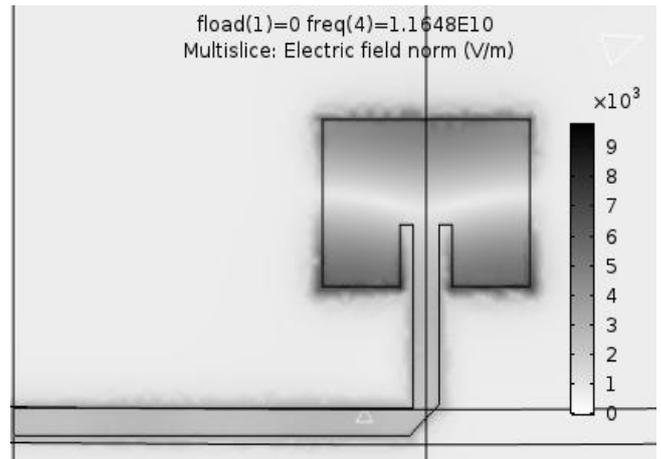


Fig. 8. Electrical field for first resonant frequency

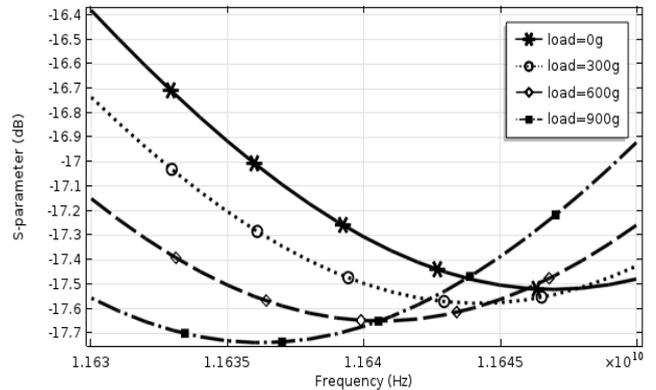


Fig. 9. Reflection coefficient S_{11} for different loads

The strain introduce the elongation of sample and sensor, therefore, shifts the antenna resonant frequency. Increasing the load causes the extension of patch antenna, thus the resonant frequency of antenna is decreasing, as presented in Figure 9. Moreover the absolute value of reflection coefficient S_{11} in case of resonant frequency is increasing under the load.

Comparison of the measurements and simulation results are presented in the Figure 10. One can observe, semi-linear dependence of resonant frequency change Δf_r on load value, as well as good agreement of simulated and measured results.

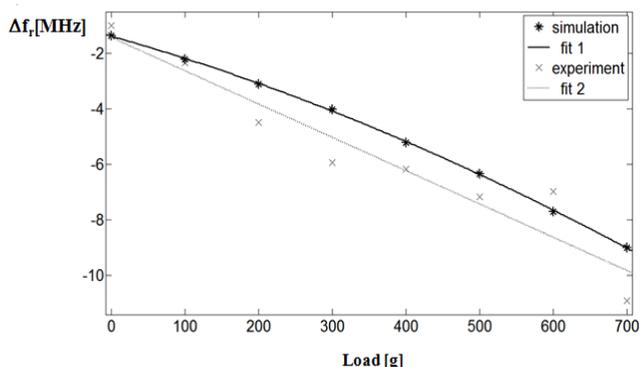


Fig. 10. Shift in the resonant frequency of microstrip sensor Δf_r .

2.2. Low frequency method

The mechanical stress introduced in the material has impact on BN and ACM signals features [4–11]. In order to estimate the influence of materials microstructure changes on magnetization process a set of 52 features, calculated from both methods signals, were used [9]. For each method the analysis of acquired signals was carried out both in time and frequency domain. In case of BN, first envelopes of BN signal and its spectrum were calculated and then the analysis of statistical and characteristic values was proceeded. Similarly in case of ACM signals the features were extracted from both time and frequency representations. Selected features distribution obtained during the experiment are presented in Figure 11. The distribution of standard deviation of BN burst envelope curve as a function of applied load is presented in Figure 11a, while in Figure 11b one can see the distribution of mean value of BN spectrum’s envelope. For the achieved features’ distribution one can observe the peak of BN activity around 600–900 gram load, which corresponding to material’s bending yield point. When material is before the yield point the activity of BN is increasing with stress, while over beyond that point the activity is decreasing with increasing plasticity of the material. Similarly, one can notice that the extreme value of first harmonic of U_H was observed in the same load range (Figure 11c). Some of achieved features presented quasi-linear trend, what can be seen in case of maximum value of U_B signal (Figure 11d).

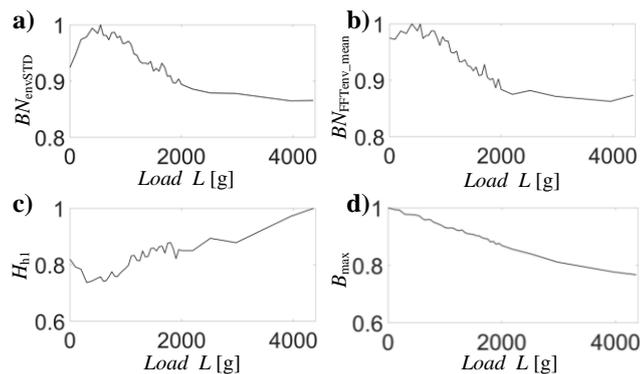


Fig. 11. Selected features distribution vs load: a) standard deviation of BN burst envelope, b) mean value of BN spectrum’s envelope, c) first harmonic of U_H signal, d) maximum value of U_B signal

None of the obtained features allow to evaluate all aspects of microstructural changes taking place in the material during loading. Therefore the need of fusion of multiple features content arises. For that purpose the data fusion algorithm based on principal component analysis (PCA) and multivariate regression was utilized. The block scheme of the introduced procedure is presented in Figure 12. First, the statistical analysis was used to select the features which presents different course with increasing loading force. On that basis 11 features out of 52 were chosen for

further analysis. Next, in order reduce dimensionality through combining most of the information content in lower number of features the PCA was applied. After the analysis the new feature vector was achieved which elements are called principal components pc [9]. The variance of the successive components of the new feature vector is presented in Figure 13. One can observe that the first two components explain over 95% of global variance of the feature vector. Therefore the two components were used in the final stage of the fusion process. The function combining the pc_1 and pc_2 component’s data was defined as:

$$W = b_0 + b_1 pc_1 + b_2 pc_2 \quad (6)$$

During the multivariate regression analysis the given b_i coefficients values were achieved to be equal to: $b_0 = 0$, $b_1 = -1,8899$, $b_2 = -0,1530$. The resulting function was plotted in Figure 14. The obtained distribution of W function presents almost characteristic changing linearly with the increase of applied load. However it is possible to observe the step changes of the function for the region of loads corresponding to elastic limit and yield banding limit of the utilized steel. Beyond the yield regions the value of W function is monotonically changing. Therefore, considering all mention aspects it is possible to evaluate the successive stages of the degradation process.

Both the simulation analysis and the experiment results demonstrate that the resonant frequency of patch antenna is sensitive to strains because of the load causes the change of patch length. Additionally, during the experiment we observed significant impact of strain into magnetic parameters thus the degradation level of steel elements can be evaluated by analysis of the changes of signals related to AC magnetization process.

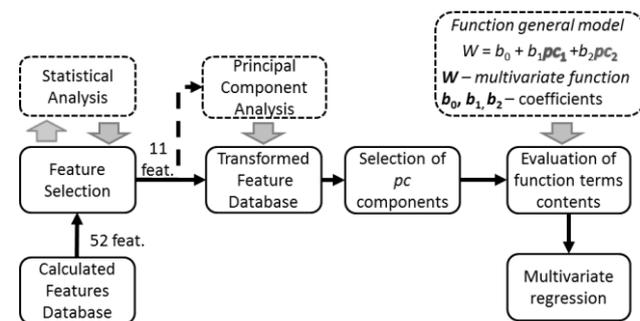


Fig. 12. Block scheme of multiple features data fusion algorithm

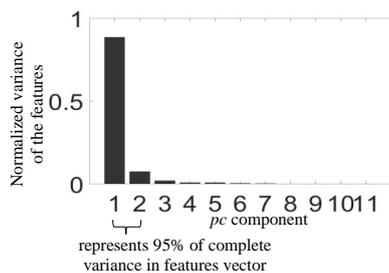


Fig. 13. Normalize variance of successive pc_i components in relation to complete variance of feature vector

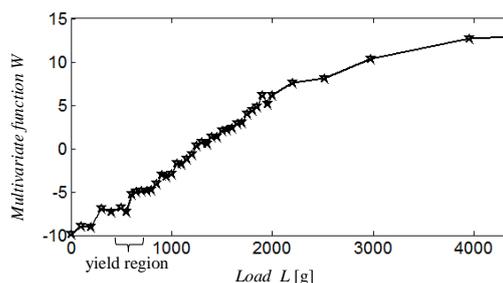


Fig. 14. The results of the multiple features function

Conclusion

The simulation and measurement based evaluation of microstrip antenna sensor proved that it can be used to detect and characterize stress in construction materials. The results of simulation and experiment demonstrate that the resonant frequency of patch antenna sensor is sensitive to strain when it applied along the direction of patch length. The first resonant frequency is decreasing under the load, whereas the shift of second resonant frequency is much smaller than the first. In the future, the substrate should be changed in order to obtain a better quality of resonance and higher stability for temperature changes. The utilization of both low frequency methods allows to monitor the microstructural changes taking place in the material under increasing loading force. The achieved features of ACM and BN makes it possible to precisely indicate reaching the yield region by the material (Figure 11). Additionally, the combination of features into one function allows to achieve not only the monotonically changing with load characteristic but also to distinguish curtail stages of the degradation process such as elastic limit or yield point.

Considering the results of both high and low frequency methods it is possible to build an inspection system which will allow to monitor even in-situ the construction state. The high frequency method results confirmed the possibility of utilization of patch antennas to control the elongation of the steel elements, where the low frequency ones correlate with the microstructural changes. Taking into consideration both aspects (indication of steel elements' dimension and microstructural changes) can lead to higher probability of proper evaluation of the construction state. The demonstrated methods are very promising in building the degradation monitoring system. In the future the further work is going to be carried out for different conditions of applied stress.

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