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Computerized Systems for Electromagnetic Nondestructive Testing

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Abstract

In this paper computerized systems for electromagnetic nondestructive testing of well- and low-conducting materials are presented. Several different inspection methods: the eddy current method, the magnetic flux leakage, the Barkhausen noise, and the AC magnetization measurement are described. Finally, the magnetic induction tomography system for evaluation of low-conductivity materials has been presented.

Keywords: electromagnetic nondestructive testing methods, eddy current method, magnetic flux leakage method, Barkhausen noise, magnetic induction tomography.

Skomputeryzowane Systemy do Elektromagnetycznych Badań Nieniszczących

Streszczenie

W niniejszym artykule przedstawiono skomputeryzowane układy do elektromagnetycznych badań nieniszczących materiałów dobrze- i słabo-przewodzących. Opisano kilka różnych metod badawczych: metodę prądów wirowych, strumienia rozproszenia, szumów Barkhausena oraz obserwacji procesu magnesowania. Zaprezentowano układ magnetycznej tomografii indukcyjnej do oceny materiałów słabo-przewodzących.

Słowa kluczowe: elektromagnetyczne metody badań nieniszczących, metoda wiroprądowa, metoda magnetycznego strumienia rozproszenia, szumy Barkhausena, magnetyczna tomografia indukcyjna.

1. Introduction

Electromagnetic techniques of nondestructive examination have gained growing attention as a result of their high operational speed and relatively low cost. These systems enable testing of very low and high conductivity materials. Several different methods have been developed and used. According to different advantages and limitations, each measuring technique provides one with the distinct range of information about the object being tested [1]. In this paper we propose to use the eddy current method, the magnetic flux leakage method, the AC magnetization measurement, and the Barkhausen noise method to estimate the material changes. Information gathered from theses techniques can be used to indicate defects with a higher probability of detection or for predicting pending failure of crucial elements.

Finally, a computerized system and a special eddy current probe suitable for inspection of low conductivity structures is presented. The probe consists of an excitation coil and two differentially connected search coils. The transducer was used to examine heterogeneities of low conductivity specimens. The test specimens were based on water solution of NaCl.

2. Computerized NDT system for metal structures evaluation

All measurements of high-conductivity structures were carried out using a new universal computerized NDT system. The system consists of positioning device (Fig. 1), a power amplifier (Fig. 2) and a PXI class system (Fig. 2) consisting of a computer unit, A/D board and an arbitrary function generator.

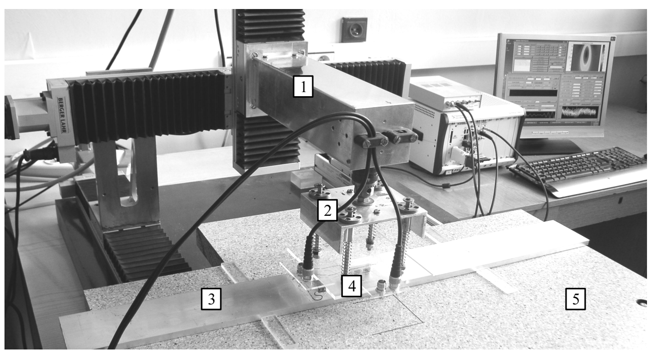

Fig. 1. Photography of the positioning device and probe (1 – XYZ scanner, 2 – flexible suspension of the probe, 3 – sample, 4 – ECT transducer, 5 – table)

Rys. 1. Fotografia układu pozycjonującego i przetwornika (1 – XYZ skaner, 2 – sprężyste zawieszenie przetwornika, 3 – próbka, 4 – przetwornik wiroprądowy, 5 – stolik)

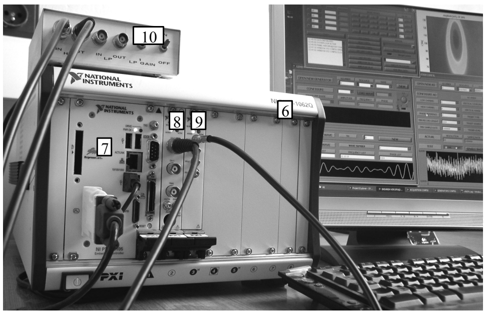

Fig. 2. Photography of computerized NDT system (6 – PXI chassis, 7 – computer unit, 8 – A/D board (NI 5922), 9 – arbitrary waveform generator (NI 5422), 10 – power amplifier)
Rys. 2. Fotografia komputerowego systemu NDT (6 – obudowa PXI, 7 – jednostka centralna, 8 – przetwornik A/C board (NI 5922), 9 – generator funkcyjny (NI 5422), 10 – wzmacniacz mocy)

Modular construction of the PXI system allows us to achieve a compact portable device retaining universality. All elements of the system are driven by a specialized program written and operating in LabView®. Through the standard controlling functions, the application allows user to collect the data acquired by A/D cards, generate multi-frequency arbitrary waveforms, analyze signals by various signal processing algorithms and visualize the data after acquisition. The software enables also to control external devices connected through the visa interface using GPIB or serial ports. User can control the system in two ways: by a graphical interface or by a dedicated script language.

3. Implemented testing methods of metal structures and exemplary results

The block diagram showing the implementation of all introduced testing methods is shown in Fig. 3. For the each method a specific transducer was proposed [1, 2]. The experiments were carried out for planar specimens made of low carbon steel (SS400). The samples were tensile deformed in the longitudinal direction. The yield of this material was around 350 MPa. The residual strain ε was between 0.7% and 14% while the maximum tensile stress σ was from 100 MPa to 389 MPa. The measurements were made by scanning the test specimen in two dimensions, along x- and y-axis.

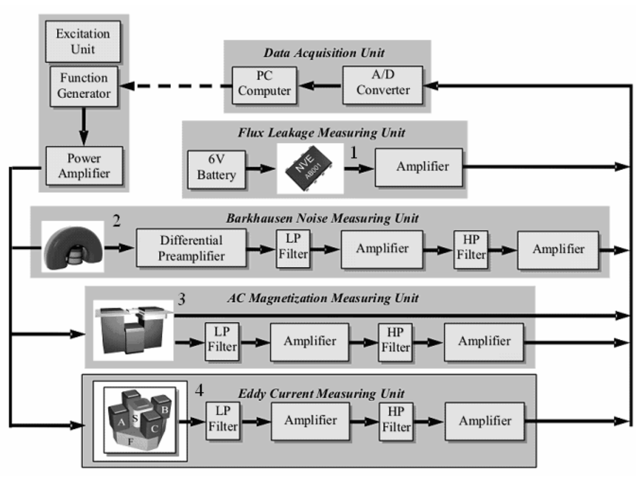

Fig. 3. Block diagram of the NDT system
Rys. 3. Schemat blokowy systemu do badań nieniszczących

Magnetic flux leakage method

A GMR gradiometer (1) shown in Fig. 3 was used to measure the flux leakage distribution [1]. As it is necessary to detect changes of the magnetic field rather than the absolute flux value, therefore a gradiometer was found to be more suitable. The GMR sensor was energized by the battery in order to avoid the noise influences from power supply unit. First, the output signal from the gradiometer was gained in power amplifier and than sampled by an A/D converter. The test samples were magnetized in longitudinal direction prior to the measurements.

AC magnetization measurements

In order to measure both: flux and magnetic field a dedicated transducer (3) shown in Fig. 3 was developed [1]. On a C-shaped ferrite core an excitation coil and flux coils were wounded. The tangential magnetic field was observed by a coil placed between the pole pieces. The excitation coil was driven by a sinusoidal current source. The output of magnetic coil was filtered and gained by two analog active filters (low-pass and high-pass) connected in series. Data from both pick-up coils were acquired by the A/D converter having two separate channels.

Barkhausen noise method

Figure 3 shows the transducer (2) used in measurements. It consists of excitation coil and two pick-up coils [1]. The excitation coil is wounded on the C-shaped ferrite core. The first pick-up coil was placed directly in the neighborhood of the specimen surface. The second one was placed above, so that it measured only unwanted interfering signals. Both pick-up coils were connected differentially. The transducer was covered by a ferromagnetic shielding box. The excitation coil was driven by a 30 Hz sinusoidal current source. The signal from the detector was fed to two analog active filters connected in series. To acquire the data, the A/D converter was used.

Eddy current method

A view of the transducer (4) is shown in Fig. 3. It consists of a ferrite core with five symmetrically placed columns [2]. A pickup coil is wounded on the central column and four excitation coils are placed on remaining columns in pairs on two perpendicular axes. One pair of the excitation coils produce in the pickup coil flux flowing in opposite direction in comparison to the flux caused by another pair. The resulting flux in the pickup coil is close to zero in an equilibrium state. The probe is sensitive to orientation of the flaws: a flaw parallel to one pair of exciting columns causes growth of the output signal's amplitude in comparison to the signal's amplitude from unflawed area. If the flaw is parallel to the second pair of columns, the output signal is decreasing. A high sensitivity to minor outer defects was achieved.

Exemplary results of the measurements carried out using all the methods are shown in Fig. 4. One can observe that the achieved results are providing complementary information and can be utilized for better evaluation of material degradation.

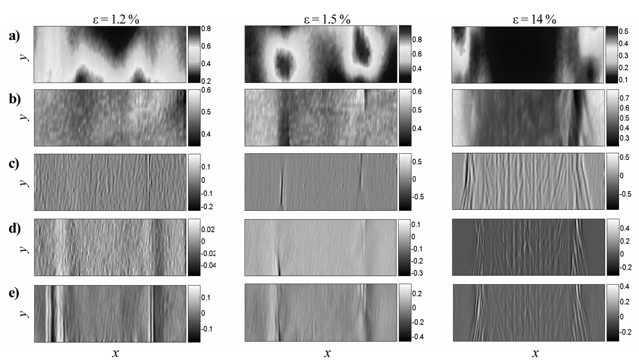

Fig. 4. Exemplary results of measurements achieved for different tensile loaded steel samples: a) energy of Barkhausen noises; b) AC magnetization observation c) flux leakage method; d) eddy current method (excitation frequency 1 kHz); e) eddy current method (excitation frequency 50 kHz)
Rys. 4. Przykładowe wyniki pomiarów otrzymane dla różnych rozciąganych próbek stalowych: a) energia szumów Barkhausena; b) obserwacja magnetyzacji c) metoda strumienia rozproszenia; d) metoda prądów wirowych (częstotliwość wzbudzenia 1 kHz); e) metoda prądów wirowych (częstotliwość wzbudzenia 50 kHz)

4. Magnetic induction tomography system for testing of low-conductivity materials

Magnetic induction tomography (MIT) is a non-contacting technique for visualization of the complex conductivity distribution inside inhomogeneous media. MIT is based on determining the perturbation of an alternating primary magnetic field by a conducting object under investigation [3-5]. This perturbation is detected by a voltage change in a receiver coil. Schematic diagram of the measurement system described in this paper is shown in Fig. 5.

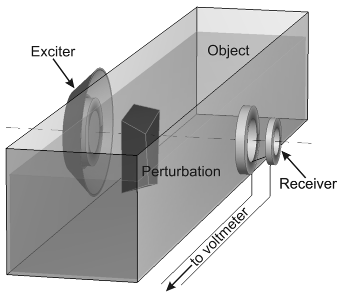

Fig. 5. Schematic diagram of the measurement system
Rys. 5. Schemat ideowy układu pomiarowego

Mathematical background

In a linear, nonmagnetic, isotropic conductive medium one can find the following equation for the magnetic vector potential **A** and the scalar potential Φ (provided that the condition $\nabla \cdot \mathbf{A} = 0$ is adopted):

$$\nabla \cdot \left[(\sigma + \varepsilon j\omega) \nabla \Phi \right] = -j\omega \mathbf{A} \cdot \nabla (\sigma + \varepsilon j\omega), \qquad (1)$$

where: σ - conductivity, ε - permittivity, ω - angular frequency. In the case if $\varepsilon\omega \ll \sigma$, (1) can be written as follows:

$$\nabla \cdot (\sigma \nabla \Phi) = -j\omega \mathbf{A} \cdot \nabla \sigma . \qquad (2)$$

Under the assumption that the object does not influence the excitation field (due to its low conductivity), the vector magnetic potential in (2) may be replaced by the primary magnetic vector potential $\mathbf{A_p}$, computed without the presence of the object. In this case the final equation has the form:

$$\nabla \cdot (\sigma \nabla \Phi) = -j\omega \mathbf{A_p} \cdot \nabla \sigma , \qquad (3)$$

with the boundary condition:

$$\frac{\partial \Phi}{\partial n} = -j\omega \mathbf{A_p} \cdot \mathbf{n} . \qquad (4)$$

The inverse field problem – reconstruction of the conductivity distribution, can be reduced to the solution of the overdetermined and ill-conditioned equation system resulting from the finite element method. This system can be solved using different regularization methods [6, 7].

Practical verification

In order to verify the theoretical considerations, the measuring system shown in Fig. 6 has been built.

The eddy current transducer utilized in the system comprises an excitation coil (1) and two pick-up coils (2 and 3). The pick-up coils are jointed together with a plastic riffle bar. All the elements are mounted together using the connecting element (4). The transducer is attached to the arm (5).

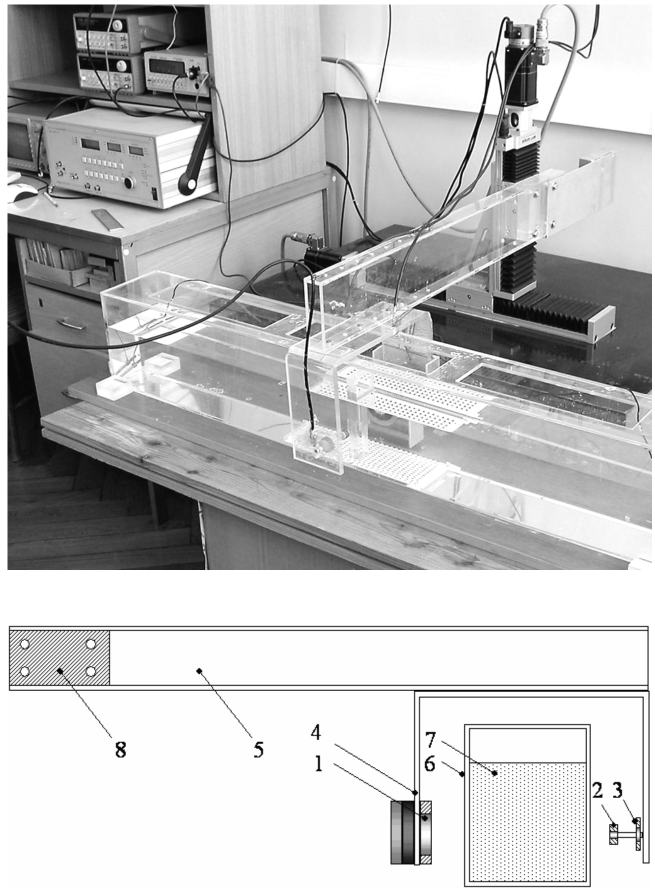

Fig. 6. Photo and view of elements of the measuring system: 1 – excitation coil; 2, 3 – two signal coils, 4 – construction element made of plexiglass, 5 – arm made of plexiglass, 6 – tank made of plexiglass, 7 – object under test, 8 – connection to XYZ scanner
Rys. 6. Zdjęcie i rzut elementów układu pomiarowego: 1 – cewka wzbudzenia; 2, 3 – dwie cewki sygnałowe; 4 – element konstrukcyjny wykonany z pleksiglasu; 5 – ramię wykonane z pleksiglasu; 6 – zbiornik wykonany z pleksiglasu; 7 – badany obiekt; 8 – połączenie do skanera XYZ

The arm (5) is linked through the part (8) with the XYZ scanner. The scanner enables movement of the transducer along the sample (6). The sensor can be moved in steps of specified length or continuously and the computer controls the scanning device. Figure 7 explains the operation of the transducer.

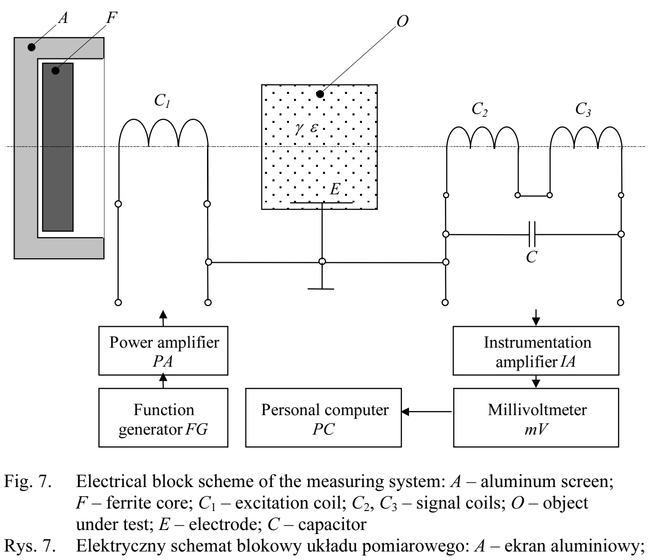

Fig. 7. Electrical block scheme of the measuring system: *A* – aluminum screen; *F* – ferrite core; C_1 – excitation coil; C_2, C_3 – signal coils; *O* – object under test; *E* – electrode; *C* – capacitor
Rys. 7. Elektryczny schemat blokowy układu pomiarowego: *A* – ekran aluminiowy; *F* – rdzeń ferrytowy; C_1 – cewka wzbudzenia; C_2, C_3 – cewki sygnałowe; *O* – badany obiekt; *E* – elektroda; *C* – kondensator

A ferrite core *F* and an aluminum screen *A* forward a magnetic flux generated by the excitation coil C_1 (n_1 = 300 turns) in direction of the pick-up coils (C_2, C_3) and the object under test. The pick-up coils C_2 and C_3 differ in number of turns (n_2 = 2000 and n_3 = 2500 respectively), cross section area and diameter. The pick-up coils are connected differentially and placed in the magnetic field generated by the excitation coil in such a way that the output voltage is close to zero. Precise selection of the positions of the pick-up coils creates opportunity to achieve a state of equilibrium. A nonzero signal from the transducers arises due to the changes of the magnetic field distribution caused by the heterogeneity of the test objects. The function synthesizer supplies the excitation coil C_1 of the transducer through a power amplifier *PA*. The pick-up coils (C_2, C_3) are connected to a capacitor *C*. The analog output signal is converted into digital form by a data acquisition subsystem. This subsystem consists of an instrumentation amplifier (*IA*) and a digital millivoltmeter. A personal computer *PC* with GPIB and serial interfaces controls the process of data acquisition, collection and presentation. The computer is driven by newly developed software written in LabView® environment.

Exemplary results of measurements are shown in Fig. 8.

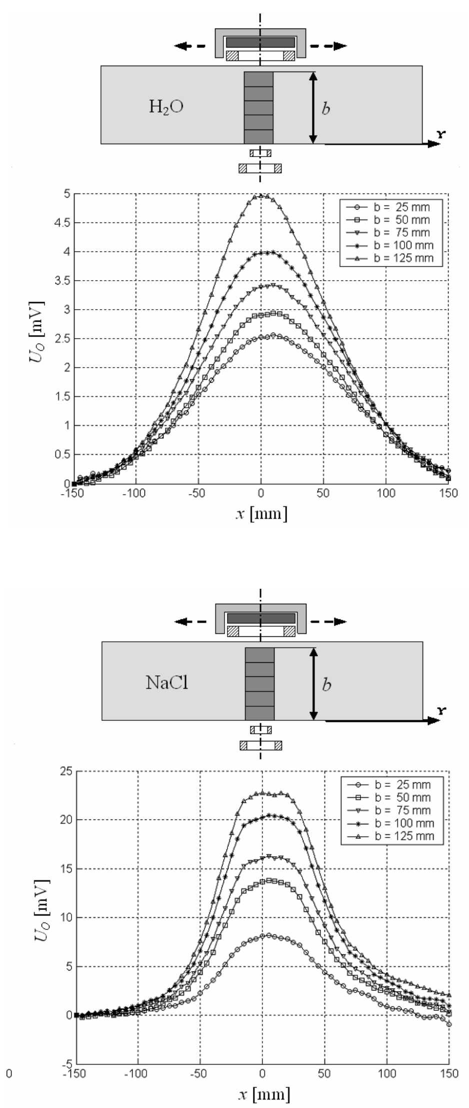

Fig. 8. Signals obtained from the transducer for different objects (the tank filed with drinking water or water solution of NaCl – concentration 20%)

Rys. 8. Sygnały z przetwornika dla różnych obiektów (zbiornik wypełniony wodą pitną lub wodnym roztworem NaCl – stężenie 20%)

The testing frequency f = 30 kHz and excitation current I_E = 20 mA were selected after preliminary tests and they were maintained during all the measurements. The transducer was scanned (± 100 mm) along the test objects (*x*-axis) in steps of 5 mm. A tank shown in Fig. 6 (length – 1200 mm, width –150 mm, height – 200 mm) filled with drinking water or water solution of NaCl was utilized as a test object. Small (length – 50 mm, width – 25 mm, height – 150 mm) nonconductive cuboids made of plexiglass were inserted into the tank in order to create local heterogeneities (Fig. 8). Figure 8 shows signals from the transducer obtained for different configuration of nonconductive cuboids placed in the tank. Top views of the cuboids configurations are shown together with the relevant plots.

5. Conclusions

Results of the experiments done for different objects and measurement strategies confirmed that proposed systems can evaluate various kinds of materials and can be applied for nondestructive testing of well- and low-conducting materials. The main advantages of the proposed systems are: flexibility, extensibility, reliability and high level of measuring process automatization.

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