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Identification of Plastic Deformations in Carbon Steel Elements Using the Filtered Barkhausen Noise Signal

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Abstract

The paper presents new approach to processing the Barkhausen Noise signal in order to detect and identify plastic deformations in carbon steel. A new automatic method of Barkhausen effect signal filtration was investigated. Apart from a classical measurement of Barkhausen effect signal, for which the RMS value is assumed, the signal waveform factor was also used in analyzes. The developed approach to processing the Barkhausen Noise signal has made it possible to obtain more useful diagnostic data than those obtained from the raw signal.

Keywords: non-destructive evaluation, plastic deformation, Barkhausen Noise, signal processing

1. Introduction

One of active diagnostic magnetic methods is Barkhausen Noise (BN) method based on the assessment of the microstructural properties of ferromagnetic materials [1]. BN is generated during jumps of magnetic domain boundaries, so-called Bloch walls, when domains set their orientation to the direction of an external magnetizing field [2, 3]. BN depends on different factors, such as material microstructure, stress state and material composition, that affect the domain structure of ferromagnetic material. Thereby, it is possible to use BN for assessment of states of the stresses and the magnitude of plastic deformations [4]. Unfortunately, the measured raw Barkhausen Noise signal often contains some components that are not related to the state of the stress and the scale of plastic deformation [5]. Therefore, it is necessary to develop an effective method of filtering the raw BN signal to remove unnecessary disturbances and obtain useful diagnostic information. The article investigates the effectiveness of the new approach to processing the Barkhausen effect signal. The use of an additional reference coil, and adaptive filtration, and Empirical Mean-based Signal Decomposition method enabled the elimination of most disturbances occurring in the raw BN signal. The filtered BN signal was used to determine a waveform factor, whose values correlate with the values of plastic deformations of carbon steel test-pieces.

2. Details of experiments

A unit generating low-frequency vibrations of the magnetic field consisted of a sinusoidal signal generator of RIGOL company, a power amplifier with amplification rate equal to 7 and a coil including 800 turns of 0.8 mm diameter winding wire wound on "UU-93-K" carcass of FERYSTER Sp. z o. o. Company. The carcass is mounted onto a "U" type core made by gluing three cores of "I" type. The channel measuring the Barkhausen effect signal uses an acoustic amplifier with amplification rate of 100 and a pickup coil built from 2400 turns of 0.15 mm diameter winding wire applied on the plastic carcass with external and internal diameters of 29 mm and 16 mm respectively and height of 15 mm. A second coil with the same parameters as the pickup coil was also connected to the measuring system. This additional coil played the role of the reference coil. The set-up was powered by a three-channel laboratory power supply TP-3305U of Twintex Company. A voltage in the form of a harmonic signal with frequency 2 Hz and amplitude 3.5 V excited vibrations of the magnetic field. Signals from both coils were recorded in digital form by the 16-channel recorder of HIOKI Company, model MR8847A, with a sampling frequency 1 MHz and with a low-pass filter (500 kHz cutoff frequency). The recording time during a single measurement was 2 s. Diagram of the set-up used for measurements is presented in Figure 1.

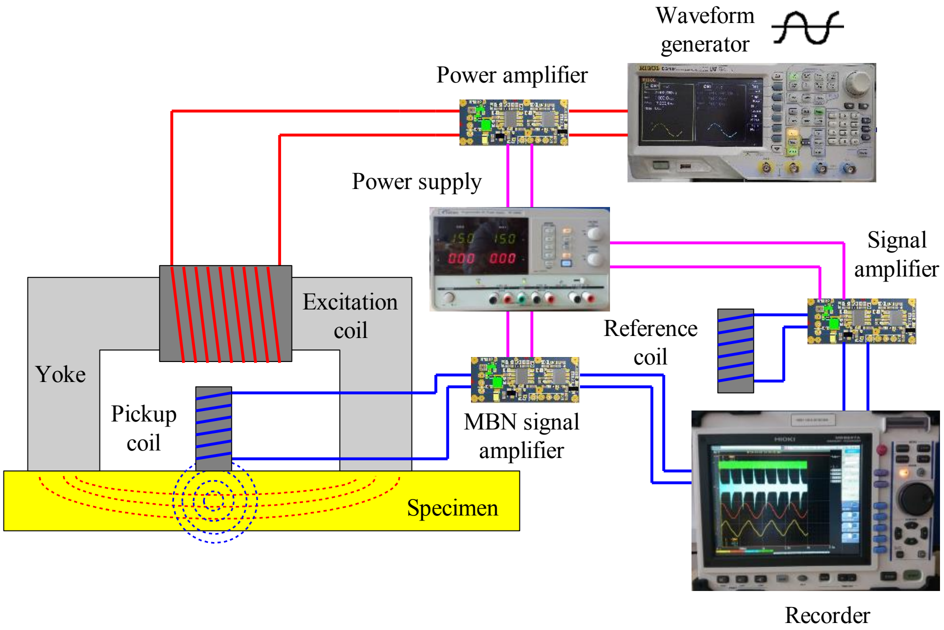

Figure 1. Block diagram of the set-up used for measurements

The carbon steel S355J2 is taken as the testing material in this study. The chemical composition of S355J2 carbon steel is as follows: carbon (C) 0.20%, sulphur (S) 0.04%, phosphorus (P) 0.04%, manganese (Mn) 1.5%, silicon (Si) 0.5%, chromium (Cr) 0.03%, nickel (Ni) 0.03%, cobalt (Co) 0.2%, copper (Cu) 0.3%. Test-pieces had dimensions 330 x 30 x 3 mm and were cut out with a guillotine from a sheet steel S355J2. The experiment was carried out with the use of Zwick-Roell Z100 testing machine in the tensile test mode. The sample was subjected to an extension test aimed to produce a plastic deformation of the sample for enabling the measurement of the magnetic effects. The plastic deformation of the test-piece has been gradually increased during the experiment. The pickup coil was mounted on the test-piece. A yoke with a coil generating low-frequency vibrations of the magnetic field (excitation coil) was placed above the pickup coil. The additional reference coil was placed outside the test-piece, at a distance of 65 mm from the pickup coil. BN signal measurements were carried out on loaded test-pieces (in-situ) at the following values of relative plastic deformations: 0 %, 1.52 %, 3.03 %, 4.55 %, 6.06 %, 7.58 % and 9.09 %.

3. Measurement results

Figures 2 and 3 show exemplary waveforms and amplitude spectra of the signals recorded by the pickup coil (BN signal) and the reference coil during the experiment. Amplitude spectra clearly show some high-frequency disturbances of varying intensity in both measured signals. In particular, there are clearly visible disturbances in the form of harmonic signals with frequencies around 16 kHz, 48 kHz and 127 kHz.

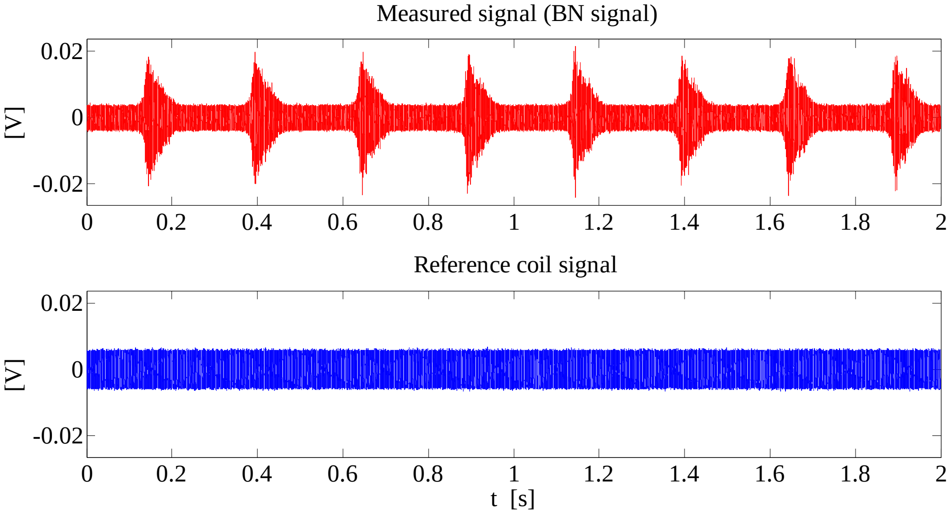

Figure 2. Waveforms of measured BN signal and reference coil signal

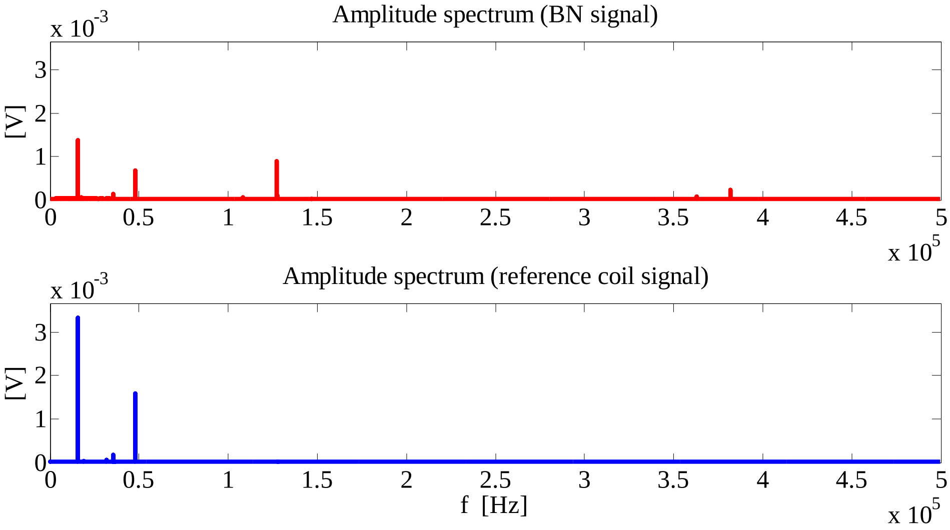

Figure 3. Amplitude spectra of measured BN signal and reference coil signal

Conventional diagnostic use of Barkhausen effect signal is based on the use of the RMS value (Root Mean Square) of the measured signal:

$$u_{\mathrm{RMS}} = \sqrt{\frac{1}{T}\int_0^T u^2(t)dt} \approx \sqrt{\frac{1}{N}\sum_{i=1}^{N} u_i^2} \tag{1}$$

where N is the number of samples and u_i are the measured values.

Figure 4 shows the correlation of the RMS value of the measured raw BN signal with plastic deformations of test-piece.

It may be noted that in the case of the plastic deformation value assessment, the RMS value of raw BN signal cannot be treated as fully useful diagnostic parameter. The RMS value of the raw BN signal does not change in a monotonic way. The poor diagnostic usefulness of raw BN signal is probably due to disturbances recorded by the pickup coil. In order to eliminate the disturbances, a two-stage BN signal filtration procedure was developed.

The first stage performs an adaptive filtration using a finite impulse response filter (FIR filter). The goal of adaptive filtering systems is to eliminate signal-disturbing components and to obtain an undisturbed desired signal [6]. The adaptive filtration scheme is shown in Figure 5.

The second stage extracts the low-frequency signal component of the FIR-filtered BN signal. An Empirical Mean-based Signal Decomposition method [7] determines this signal using the technique introduced in Empirical Mode Decomposition method for empirical determination of signal envelopes [8]. The processing algorithm of the FIR-filtered BN signal consists of the following steps:

Step 1: Identification of all local extremes (maxima and minima) of FIR-filtered signal $x(t)$.

Step 2: Connecting all local maxima (respectively minima) with a line known as the empirically determined upper envelope $E_U(t)$ (respectively the lower envelope $E_L(t)$). Local maxima (minima) are connected with a line by using piecewise cubic interpolation (Piecewise Cubic Hermite Interpolating Polynomials – PCHIP).

Step 3: Constructing the mean of empirically determined upper and lower envelopes (the low-frequency signal component) $d(t) = 0.5\cdot(E_U(t) + E_L(t))$. The low-frequency component of the FIR-filtered BN signal is treated as the (finally) filtered BN signal.

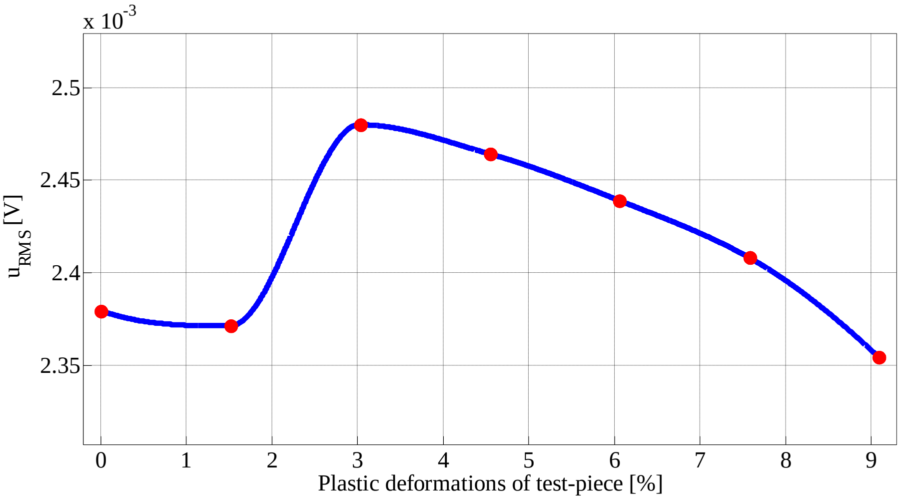

Figure 4. Dependence of RMS value of the measured BN signals on plastic deformations of test-piece

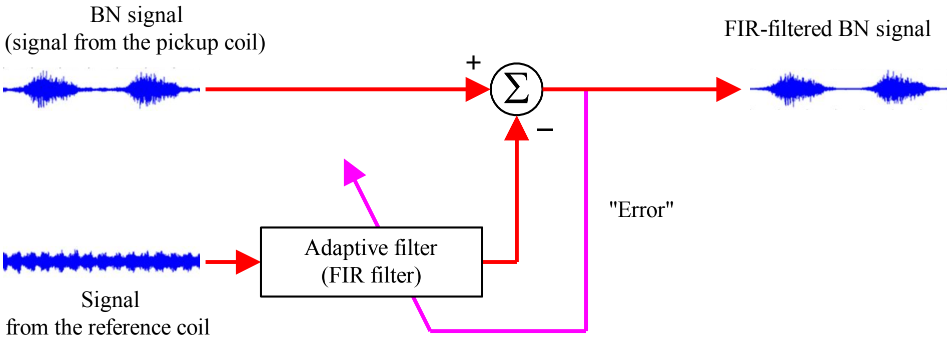

Figure 5. Adaptive filtration scheme

Figure 6 and 7 show waveforms and amplitude spectra of exemplary raw and filtered BN signals. It is clearly visible how the level of disturbances in the filtered BN signal is reduced. This creates a possibility for a better use of the diagnostic information contained in the Barkhausen effect signal.

Based on the filtered BN signal, the waveform factor was determined, defined by the formula:

$$u_{\mathrm{WF}} = \frac{u_{\mathrm{RMS}}}{u_{\mathrm{AVE}}} = \frac{\sqrt{\dfrac{1}{T}\displaystyle\int_0^T u^2(t)dt}}{\dfrac{1}{T}\displaystyle\int_0^T \left|u(t)\right|dt} \approx \frac{\sqrt{\dfrac{1}{N}\displaystyle\sum_{i=1}^{N} u_i^2}}{\dfrac{1}{N}\displaystyle\sum_{i=1}^{N} \left|u_i\right|} \qquad (2)$$

where N is the number of samples and u_i are the measured values.

Figure 8 shows the correlation of the waveform factor of the filtered BN signal with plastic deformations of test-pieces. It may be noted that the waveform factor of the filtered BN signal can be treated as fully useful diagnostic parameter. The monotonic change in the waveform factor value and the correlation of its value with the plastic deformation of the test-piece is clearly visible.

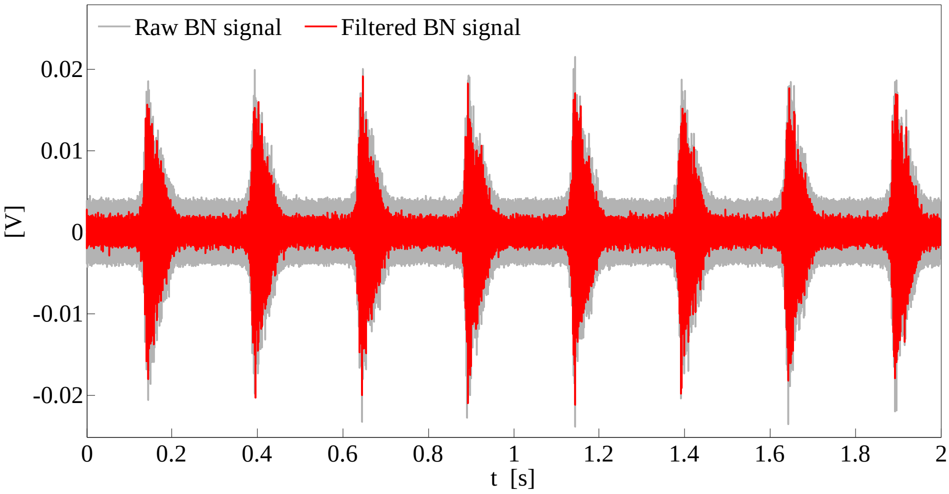

Figure 6. Waveforms of exemplary raw BN signal and filtered BN signal

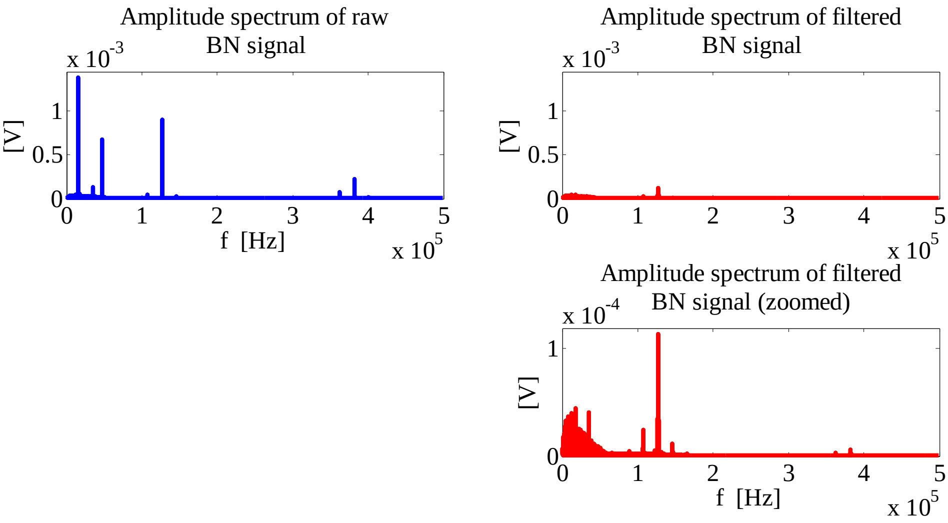

Figure 7. Amplitude spectra of exemplary raw BN signal and filtered BN signal

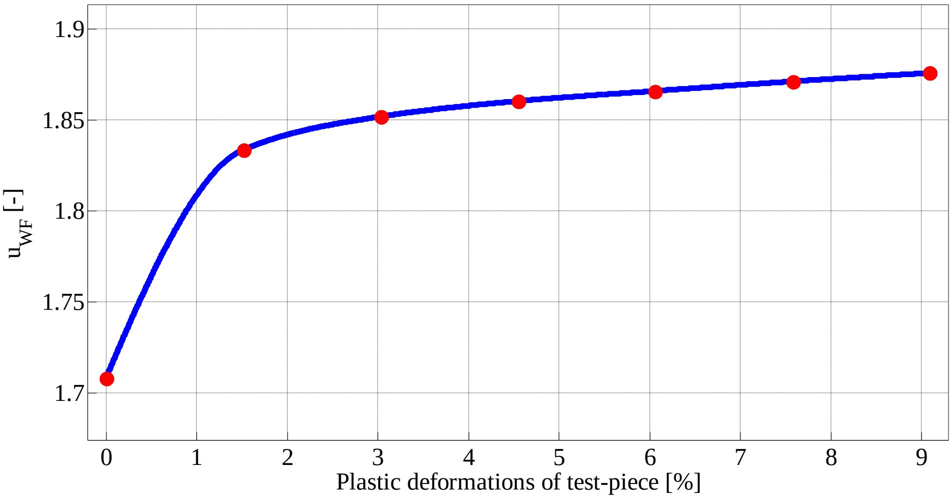

Figure 8. Dependence of waveform factor of the filtered BN signals on plastic deformations of test-piece

4. Conclusions

The original method of the Barkhausen effect signal filtration was developed to eliminate disturbances present in the signal recorded by the pickup coil. It was proved that applied filtration of BN signal led to better use of diagnostic information contained in this signal. In case of the necessity to assess the plastic deformation value of the element made of carbon steel, the waveform factor of the filtered BN signal can be treated as useful diagnostic parameter. The waveform factor is a diagnostic parameter convenient for interpretation, because its value is positively correlated with the amount of plastic deformation (its value increases with the increase in the value of plastic deformation).

References

1. J. C. Sánchez, M. F. Campos, L. R. Padovese, *Magnetic Barkhausen emission in lightly deformed AISI 1070 steel*, Journal of Magnetism and Magnetic Materials, **324**(1) (2012) 11 – 14, https://doi.org/10.1016/j.jmmm.2011.07.014.
2. D. C. Jiles, *Dynamics of domain magnetization and the Barkhausen effect*, Czechoslovak Journal of Physics, **50**(8) (2000) 893 – 924, https://doi.org/10.1023/A:1022846128461.
3. S. Santa-aho, A. Laitinen, A. Sorsa, M. Vippola, *Barkhausen Noise Probes and Modelling: A Review*, Journal of Nondestructive Evaluation, **38**(94) (2019), https://doi.org/10.1007/s10921-019-0636-z.
4. H. Chen, S. Xie, Z. Chen, T. Takagi, T. Uchimoto, K. Yoshihara, *Quantitative nondestructive evaluation of plastic deformation in carbon steel based on electromagnetic methods*, Materials Transactions, **55**(12) (2014) 1806 – 1815, https://doi.org/10.2320/matertrans.M2014173.
5. D. Blažek, M. Neslušan, M. Mičica, J. Pištora, *Extraction of Barkhausen noise from the measured raw signal in high-frequency regimes*, Measurement, **94** (2016) 456 – 463, http://dx.doi.org/10.1016/j.measurement.2016.08.022.
6. B. Widrow, J. R. Glover, J. M. McCool, J. Kaunitz, C. S. Williams, R. H. Hearn, J. R. Zeidler, E. Dong Jr., R. C. Goodlin, *Adaptive Noise Cancelling: Principles and Applications*, Proceedings of the IEEE, **63**(12) (1975) 1692 – 1716, http://dx.doi.org/10.1109/PROC.1975.10036.
7. J. Dybała, J. Komoda, *Empirical signal decomposition methods as a tool of early detection of bearing fault*, in: Eds. A. Timofiejczuk, F. Chaari, R. Zimroz, W. Bartelmus, M. Haddar, Advances in Condition Monitoring of Machinery in Non-Stationary Operations, Applied Condition Monitoring, **9**, Springer International Publishing AG, Cham 2018, 147 – 156, https://doi.org/10.1007/978-3-319-61927-9_14.
8. N. E. Huang, Z. Shen, S. R. Long, M. C. Wu, H. H. Shih, Q. Zheng, N. C. Yen, C. C. Tung, H. H. Liu, *The empirical mode decomposition and the Hilbert spectrum for nonlinear and non–stationary time series analysis*, Proceedings of the Royal Society of London, Series A – Mathematical, Physical and Engineering Sciences, **454**(1971) (1998) 903 – 995, http://dx.doi.org/10.1098/rspa.1998.0193.