Influence of Magnetizing and Filtering Frequencies on Barkhausen Noise Response

Oleksandr Stupakov[1] and Yevgen Melikhov[2]

[1]Institute of Physics, Academy of Sciences of the Czech Republic, Prague 18221, Czech Republic
[2]Wolfson Centre for Magnetics, Cardiff University, Cardiff CF24 3AA, U.K.

This paper is devoted to frequency issues of the Barkhausen noise (BN) measurements, namely, to investigation of influence of magnetizing and filtering frequencies on the BN response. The measurements were performed for typical industrial steels at controllable magnetizing conditions: fixed induction or field waveforms. A vertically mounted array of three Hall sensors was used for direct determination of the sample magnetic field. The BN signal was detected locally by a surface-mounted pancake coil. In ac magnetizing frequency range, the BN quantities were observed to follow a nearly square root dependence on the frequency, provoking the classical discussion about possible correlation between the magnetic hysteresis and the BN effects. Influence of the filtering frequencies on the BN parameters (reading depth adjustment) was studied on a decarburized spring steel with surface ferrite layers of different thicknesses.

Index Terms—**Barkhausen effect, filtering, frequency measurement, magnetic field measurement.**

I. INTRODUCTION

THE MAGNETIC Barkhausen noise (BN) method is known to be sensitive to commonly occurred variations of the magnetizing-sensing conditions. The dependence of the BN signal on the magnetizing frequency is important for physical interpretation of the experimental data and for stabilization of the BN measurements in industrial environment [1]–[3]. Small variations of the BN sensor liftoff can lead to substantial changes of the magnetizing speed and amplitude. This issue becomes very important when the method is applied for nondestructive evaluation. The commercial attachable sensors are usually of small size to satisfy the industrial requirements (small samples of irregular shapes); such sensors are very sensitive to frequently occurred variations of the liftoff [1]. The band-pass filtering is the other important factor as it is used to get rid of a hysteresis signal and its harmonics on the low-frequency side and to suppress a parasitic background noise on the high-frequency side. However, the filtering parameters also influence the BN signal and its reading depth [3], [4].

This paper focuses on these two particular problems of the BN measurements: 1) dependence of the BN signal on the magnetizing frequency and 2) reasonable choice of the band-pass filtering frequencies and a filter type. The key point of our measurement approach is that the BN is measured at fully controllable magnetizing conditions: the waveform of the magnetic flux or field is adjusted to a prescribed sinusoidal/triangular shape. Moreover, the subsurface BN signal picked up by an attached bobbin coil is referred to the directly measured surface magnetic field [5]. This approach is expected to provide the true data needed for correct physical interpretation and to minimize the measurement error caused by the sensor liftoff variations [6], [7].

II. EXPERIMENT

Different Fe-based construction materials from the magnetically soft electrical steels with the coercive field $H_c \simeq$ 20–50 A/m to much harder Transformation Induced Plasticity (TRIP) and spring steels were tested. The dependence of the BN response on the magnetization frequency measured with the fixed sinusoidal $B(t)$ waveform was presented for typical non-oriented (NO) and grain-oriented (GO) steels; according to the IEEE standards, the electrical steels should be tested at 50 Hz sine flux waveform [5], [8]. Other magnetizing frequency relations for the magnetically harder micro-alloyed and TRIP steels with $H_c \simeq 250$ and 800 A/m, respectively, were obtained at triangular $H(t)$ waveforms. The surface field control is a more attractive approach from the application point of view; it is technically difficult to evaluate the bulk magnetization of industrially shaped samples. The thicknesses of the GO, NO, and harder samples were 0.3, 0.5, and 0.9 mm, respectively. Influence of the filtering frequencies on the BN parameters was studied on the decarburized spring steel with surface ferrite layers of different thicknesses (the coercivities of the bulk material $H_c \simeq 1100$ A/m and of the ferrite layers $H_c \simeq 100$ A/m) [9].

The technical details of the setup were comprehensively discussed in [3] and [5]; only the necessary experimental parameters are specified below. Flat samples were magnetized by a single Fe–Si yoke. The magnetic induction B was measured by a sample-wrapping coil. A tangential surface field profile at 1.5, 4.5, and 7.5 mm above the sample was measured by a vertically mounted array of three Hall sensors. The actual sample field H was determined by linear extrapolation of the measured field profile to the sample face. The waveform of $B(t)$ or $H(t)$ was iteratively adjusted to the prescribed sinusoidal/triangular curve by means of a digital feedback procedure [6], [7]. A simple algorithm based on a direct correction of the magnetizing voltage signal according to the difference between the actual and the desired waveforms was utilized. However, this feedback algorithm is effective

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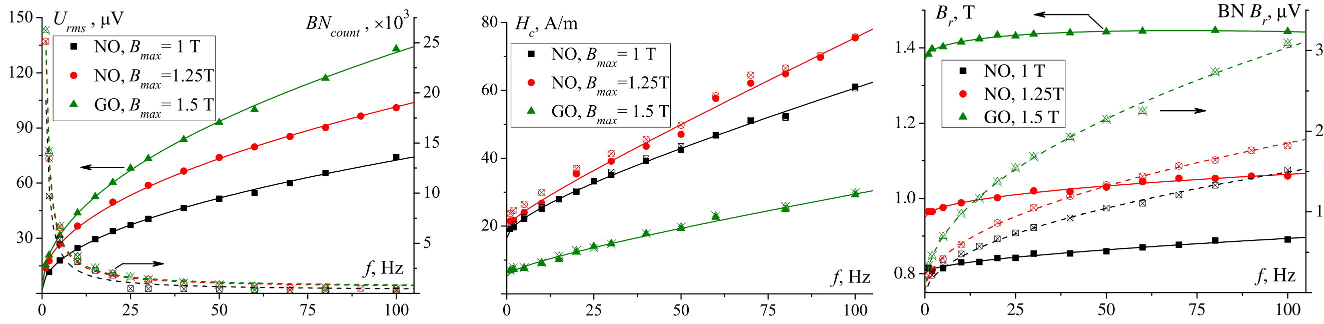


(a) (b) (c)

Fig. 1. Dependence of the typical BN and hysteresis parameters on the magnetizing frequency f for the electrical NO and GO steels. (a) BN rms value U_{rms} (solid symbols, left scale) and BN impulse count $\mathrm{BN}_{\mathrm{count}}$ (hollow symbols, right scale). (b) Hysteresis and BN coercivities H_c (solid and hollow symbols, respectively). (c) Hysteresis and BN remanences B_r (solid symbols referred to the left scale and hollow symbols referred to the right scale, respectively). The data for the NO steel are presented for the two magnetic induction amplitudes $B_{\max} = 1$ and 1.25 T; the GO steel data are presented for $B_{\max} = 1.5$ T only. All shown curves present the best data fitting. U_{rms} and BN B_r data are fitted by the simple square root function $a\sqrt{f} + c$ with the Pearson correlation coefficient $R = 0.999 - 0.9997$. H_c and hysteresis B_r data are fitted by the standard formula $a\sqrt{f} + bf + c$ with $R = 0.994 - 0.999$. $\mathrm{BN}_{\mathrm{count}}$ data are fitted by the reciprocal function $a/f + c$ with $R \simeq 0.998$.

at low magnetizing frequencies f and fails at some critical f_c value. For the electrical steels with the $B(t)$ control, $f_c \simeq$100–200 Hz; for the harder tested steels with the $H(t)$ control, $f_c \simeq$5–10 Hz only [5]. A more complicated feedback procedure taking into account the phase lags between the signals is under development.

The BN was measured by a surface-mounted pancake coil of 1000 turns with a core from laminated GO steel. The cross section of the core was 4×4 mm^2 and the outer diameter of the coil was 16 mm. The BN signal was amplified by 2000–5000 times, band-pass analogue filtered, digitized with a 500 kHz sampling rate, digitally filtered in the bandwidth of ∼2–50 kHz (the coil resonance frequency is ∼130 kHz), and finally averaged over ∼100 magnetization cycles. A broad set of different BN parameters was analyzed; however, the results were presented for four characteristic quantities, which can demonstrate qualitatively different behavior: 1) the classical rms value of BN per one magnetization cycle, U_{rms}; 2) the number of BN impulses above the selected background level of 20 μV, $\mathrm{BN}_{\mathrm{count}}$; and 3) and 4) the hysteresis-like parameters, BN coercivity H_c, and remanence B_r, obtained from the integral of a BN envelope (BN rms profile), U_{env}, which gives a hysteresis-like BN loop. The BN H_c seems to correspond to the surface hysteresis coercivity. The BN B_r was normalized to the magnetization period [8], [10].

III. RESULTS

Fig. 1 presents the dependence of the typical BN and hysteresis parameters on the magnetizing frequency f for the electrical steels measured with the fixed sinusoidal $B(t)$ waveform. Level of the BN signal (U_{rms} and BN B_r) grows more rapidly with f increase as compared with the hysteresis data (B_r). It is surprising that the above-mentioned BN relations are well fitted by a simple square root function. The BN H_c does not depend on the BN signal level but only on the BN envelope shape; it follows the hysteresis H_c dependence with a good accuracy [8], [10]. For the $\mathrm{BN}_{\mathrm{count}}$ data, the fitting by the reciprocal function is found to be more suitable than the fitting by the exponential function, but it does not give a perfect fit at high f.

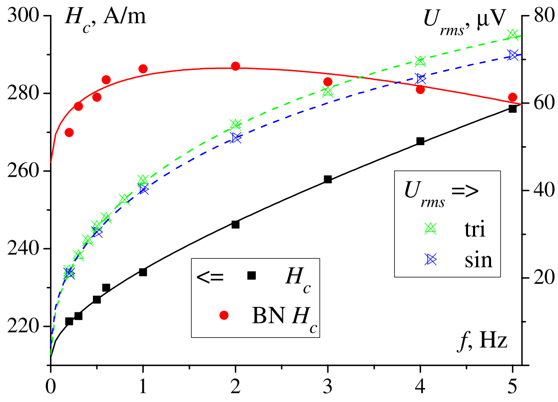
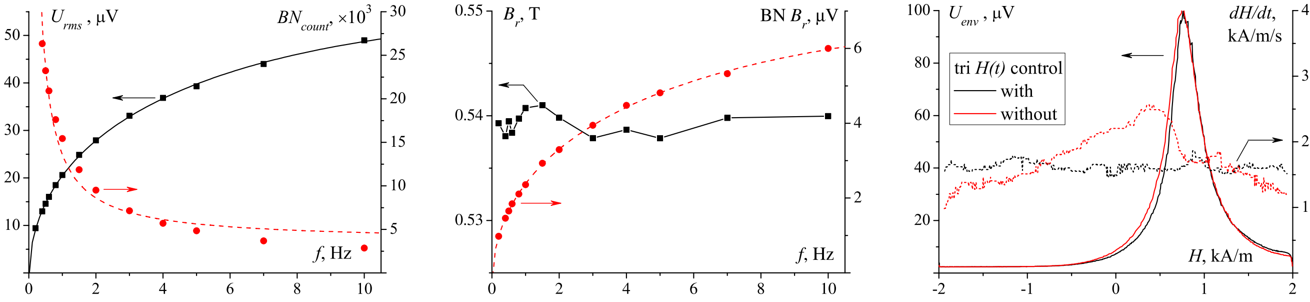


Fig. 2. Similar magnetizing frequency dependence of hysteresis and BN H_c (left scale) as well as rms value U_{rms} (right scale) for the micro-alloyed steel. The U_{rms} data are presented for the measurements with the adjusted triangular and sinusoidal shapes of the surface magnetic field $H(t)$. All data are fitted by the standard formula $a\sqrt{f} + bf + c$; $R = 0.9994$ for the hysteresis H_c data, $R = 0.91$ for the BN H_c data, and $R \simeq 0.9997$–0.9999 for the U_{rms} data.

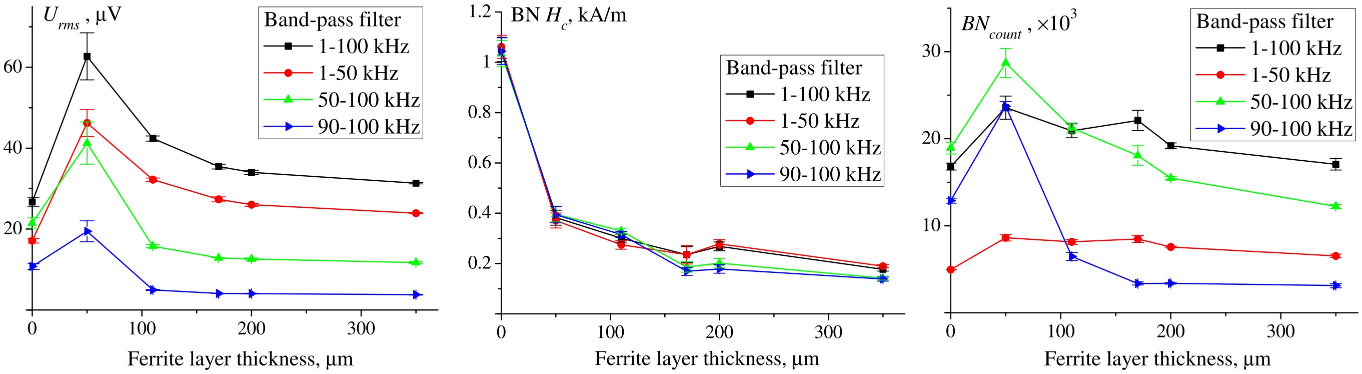
Fig. 2 shows similar typical relations for the magnetically harder micro-alloyed steel. For the twice thicker micro-alloyed sample, higher eddy currents lead to more inhomogeneous bulk magnetization and therefore to the different behavior of the bulk hysteresis and the surface BN coercivities [1], [2]. The hysteresis H_c grows according to the standard formula $a\sqrt{f} + bf + c$, whereas the BN H_c is nearly constant in the considered frequency range of $f \le 5$ Hz. The U_{rms} dependence for the fixed sinusoidal $H(t)$ waveform is shown for comparison. It is qualitatively very similar to the dependence obtained at the triangular $H(t)$; the U_{rms} values are slightly smaller for the sinusoidal $H(t)$ because of a lower magnetizing rate dH/dt. Both U_{rms} relations are fitted by the standard hysteresis formula $a\sqrt{f} + bf + c$; the linear coefficient b is negative and by one order of magnitude smaller than the square root coefficient a.

Fig. 3(a) and (b) presents similar frequency relations for the magnetically hardest TRIP steel. Despite the fact that the



(a) (b) (c)

Fig. 3. Similar magnetizing frequency dependence of the BN and the hysteresis parameters for the hardest TRIP steel. (a) BN rms value $U_{\rm rms}$ (square symbols, left scale) and BN impulse count $\rm BN_{count}$ (circle symbols, right scale). (b) Hysteresis and BN remanences B_r (square symbols referred to the left scale and circle symbols referred to the right scale, respectively). The curves present the best data fitting. $U_{\rm rms}$ and BN B_r data are fitted by the standard formula $a\sqrt{f}+bf+c$ with $R=0.9998$. $\rm BN_{count}$ data are fitted by the reciprocal function $a/f+c$ with $R=0.986$. (c) BN envelopes $U_{\rm env}$ (solid lines, left scale) and the corresponding field rates dH/dt (dotted lines, right scale) for the measurements with and without the $H(t)$ control.



(a) (b) (c)

Fig. 4. Dependence of the characteristic BN parameters on the surface ferrite layer thickness for the decarburized spring steel. (a) BN rms value $U_{\rm rms}$. (b) BN coercivity H_c. (c) BN impulse count $\rm BN_{count}$. The measurements were performed at $f=0.5$ Hz for the different filtering frequencies, which are shown in graph labels.

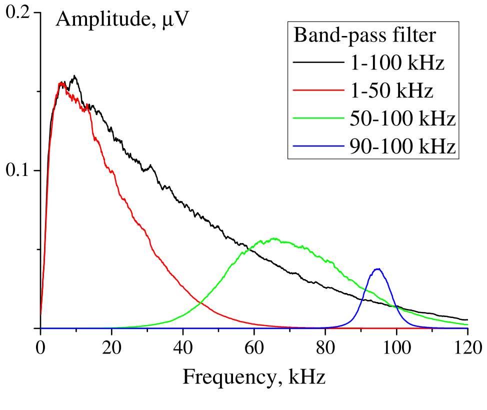


Fig. 5. Filtered BN spectra for the measurements shown in Fig. 4. The Bessel filter type was used.

magnetic hysteresis parameters as well as the BN H_c do not change in the considered frequency range of $f \leq 10$ Hz, the BN quantities behave similar: $U_{\rm rms}$ and BN B_r are well fitted by the standard formula; the linear coefficient b is negative and by one order of magnitude smaller than the square root coefficient a. Fig. 3(c) clearly shows dependence of the BN response on the magnetizing speed dH/dt; the speed influence is more evident in the region of the BN envelope peak.

Fig. 4 demonstrates the measurement results obtained with the different band-pass filtering frequencies. Narrower band-pass filtering of a slowly decaying BN spectra leads to decrease of the detected BN signal. It is well illustrated by Fig. 4(a): the $U_{\rm rms}$ relations are qualitatively similar, but their sensitivity to the tested structure changes deteriorates with the band-pass narrowing. On the contrary, BN H_c is hardly influenced by the filtering; however, the high-frequency filtering results in more monotonous decaying with the ferrite layer thickness, which is a physically expected trend [9]. The $\rm BN_{count}$ parameter demonstrates an unstable behavior, which can be a consequence of using the Bessel filter (Fig. 5).

IV. CONCLUSION

Dynamical behavior of the BN response is a scantily studied issue [11], [12]. Physically correct investigations of this problem require the experimental data obtained at fixed magnetizing waveform [2], [6]. This paper presents the first attempt to perform such a study. The measurements of the electrical steels performed in the broad ac frequency range with the sinusoidal $B(t)$ waveform reveal the root square dependence of the BN response [Fig. 1(a) and (c)]. If an analogy with the hysteresis loss separation theory could be drawn, the $\sqrt{f}$ term would correspond to the excess loss arising from the eddy currents surrounding the moving domain walls [2], [12]. Hence, this dependence can be explained recalling that the BN originates from rapid irreversible motions of the domain walls. For the measurements of the magnetically harder steels with the fixed $H(t)$ waveforms, the fitting procedure adds the nonphysical linear classical-loss term with the parameter b being negative but rather small [Figs. 2 and 3(a) and (b)]. This is most likely due to the different fixation of the magnetizing waveform (the loss separation theory is valid for the $B(t)$ fixation only) or due to a higher contribution related to the 180° domain wall motion [2]. Further detailed study is needed to propose a more physically based fitting. Finally, the BN signal level tends to zero at $f \to 0$: the fitting coefficient $c = 1$–5 and 0.2–0.4 μV for U_{rms} and BN B_r data, respectively; these are on the level of background noise.

The $\mathrm{BN_{count}}$ is another classical parameter, which can provide an additional information to the rms value and profile. However, the first problem is a BN impulse overlapping leading to the rapid decrease of the $\mathrm{BN_{count}}$ value even at a few hertz magnetizing frequency [Figs. 1(a) and 3(a)]. The second problem is a proper choice of the background noise threshold, which can significantly influence the $\mathrm{BN_{count}}$ value [3], [13]. In addition, the last problem is a correct choice of the filter type. The Bessel filter is frequently used because of a maximally flat phase delay; however, its slowly decaying frequency response can lead to different $\mathrm{BN_{count}}$ dependence [Figs. 4(c) and 5]. To obtain the stable $\mathrm{BN_{count}}$ data, it could be better to neglect the phase delay mistake and to use the Butterworth filter with a maximally flat frequency response [3].

The recently introduced BN H_c parameter proves its correspondence with the subsurface coercive force. For the thin electrical steel sheets, which were magnetized nearly homogeneously, there is practically a unique correspondence between the hysteresis and the BN coercivities [Fig. 1(b)] [8], [10]. For the thicker micro-alloyed sample, the eddy currents do not appreciably influence the surface magnetization, which results in nearly constant BN H_c (Fig. 2). The small BN H_c increase of ~15 A/m at $f \to 1$ Hz is due to an insufficient signal-to-noise ratio and the corresponding error at the BN envelope integration. The following BN H_c decrease of ~10 A/m at $f \to 5$ Hz is probably caused by a slightly weaker magnetization of the subsurface sample layers. For the hardest TRIP steel, both coercivity parameters are constant in the considered frequency range of $f \le 10$ Hz: hysteresis $H_c \simeq 780$ A/m and BN $H_c \simeq 805$ A/m. The obtained shift between the hysteresis-BN coercivities is probably due to the above-mentioned factors: the inhomogeneous bulk magnetization due to the eddy currents or the background noise contribution masking the small BN jumps at high fields. In addition, the high frequency filtering leads to decrease of the BN reading depth and therefore can improve the method sensitivity for detection of the treated surface layers [Fig. 4(b)] [4].

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