Determinism and correlation dimension of Barkhausen noise

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(Received 1 December 1997; revised manuscript received 23 February 1998)

Barkhausen noise (BN) is measured in an amorphous ribbon in an open magnetic circuit. The experiment is set up in such a way as to obtain the BN signal with a high frequency range and low apparatus noise. The driving field is produced by a pair of Helmholtz coils and the pick-up coil is a low capacity radio coil. The signal is amplified by a custom designed two-stage, battery operated amplifier, which together with the coils and the ferromagnetic ribbon is screened by three coats of soft iron. The data acquisition is done by a 12-bit analog-digital card allowing one to obtain up to 1×10^6 data points with a sampling frequency up to 1 MHz. The correlation dimension of the BN signal is calculated using the Grassberger-Procaccia algorithm and the surrogate data method is used to exclude artifacts. The choice of the measurement conditions and the calculation parameters is discussed. The results show a low dimensionality of the Barkhausen noise that leads to the conclusion that the effect may contain or is caused by a deterministic mechanism. The experimental method allows one to obtain the BN signal over many magnetic reversals so that the repeatability of the results is shown and statistics on the correlation dimension values are performed. [S1063-651X(98)06106-6]

PACS number(s): 05.40.+j, 75.60.Ej, 05.45.+b

I. INTRODUCTION

Barkhausen noise is observed as irregular voltage pulses in a pickup coil placed near a ferromagnetic specimen driven by an external magnetic field varying smoothly in time. The effect results from the microstructure of the hysteresis loop, therefore it may help in the understanding of the dynamical properties of the magnetization process.

The physical properties of Barkhausen noise (BN) have been studied since 1919 [1,2] but there is still no consensus on a standard model. It is usually considered that the main process causing it is an irregular motion of domain walls. The other possible processes contributing to BN may be the irreversible, sudden, and discontinuous rotations of the magnetization vector in materials with anisotropy, domain creation-annihilation processes, or pinning effects due to disorder and impurities. The occurrence of specific contributions to the BN mechanisms depends on the material and the participation of particular factors changes as the magnetization process proceeds.

The most characteristic features of the observed BN are $1/f$ behavior of the power spectra at high frequencies [2–4] and the fractal geometry of the shape of the signal [5]. These features seem to explain recent results of the investigations of the Barkhausen noise, which may be divided into three groups.

Firstly, the noise may be treated as stochastic [3]. It is then modeled by equations containing stochastic elements with parameters fitted in such a way as to get the desired shape of the power spectra.

On the other hand, a $1/f$ power spectrum might be evidence for self-organized criticality, and recently much work has been focused on this approach [6,7]. There are, in fact, physical considerations that support this point of view. The Barkhausen effect is a collective phenomenon in which a small perturbation to a single domain may spread to its neighbors, causing an avalanchelike propagation without any characteristic time or range constants. The size of the avalanche depends on a local instability of the domain structure and its lifetime reflects the relaxation time of the system. In some materials, the clusterlike structure of domain boundaries [3,5] additionally intensifies such self-organization.

Note that the use of power spectra for BN analysis is complicated by the wide range of scaling exponents obtained in the experimental observations [4]. Below, for comparison, we calculate the power spectra for our measurements (Sec. III A).

Finally, Barkhausen noise may be treated as a nonlinear, nonstationary phenomenon that reflects the complex dynamics of the physical system. It has been shown [8–10] that the equations of motion of a single domain wall may exhibit chaotic solutions. This result and also the presence of long-range magnetostatic interactions leads to the conclusion that the nature of the irregularity of the BN pulses may be deterministic and not necessarily depend significantly on the random disorder of the material. In other words, chaos in the BN pulses may need to be treated as deterministic rather than stochastic.

The problem of determinism in the Barkhausen noise has been recently discussed in several papers considering the reproducibility of BN patterns (see [11–13] and references therein). It has been found that under specific conditions (slow sweeping over a minor hysteresis loop) the patterns were highly reproducible. These results were found to be only weakly dependent on the temperature and the driving rate but the patterns observed were strongly determined by the range of the sweep field. Therefore the reproducibility was considered to be a consequence of dynamical effects.

The main purpose of this work is to show that the dynamics of the Barkhausen effect exhibits low dimensionality and, therefore, can be treated as a deterministic chaotic phenom-

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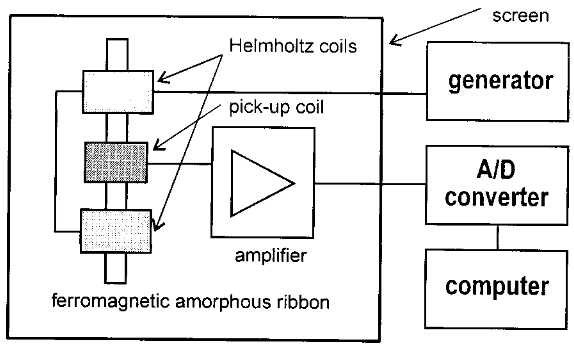

FIG. 1. The experimental setup to measure Barkhausen noise in an amorphous ferromagnetic ribbon.

enon. We have analysed 50 full cycles of magnetization reversal in an amorphous ribbon at a moderately high magnetization rate (up to 10 Hz) and discuss the reproducibility of the Barkhausen noise obtained. We then show that the phenomenon has a low number of degrees of freedom—the correlation dimension for the signal measured is low (about 3). We demonstrate that Barkhausen noise is a deterministic phenomenon by the use of an appropriate surrogate data technique. Finally, applying a unique embedding we obtain indications that an attractor for the Barkhausen noise exists—in spite of the fact that in our experiment the sample is fully saturated at the end of each magnetization cycle.

Correlation dimension (Sec. III B) is one of the fractal measures usually used for the investigation of chaos in experimental data [14]. It should be stressed that this measure cannot be directly compared with other fractal dimensions like those in the Refs. [5] and [15] because in each of them a different sense of fractality in the signals measured is calculated. In Ref. [15], the authors use a dimension defined as the slope of the function $\ln[N(m)]$ versus $\ln(m)$, where m is the increment of the magnetization caused by the increase of the magnetic field and $N(m)$ is the cumulative number of data that have the value larger than a given m. The Minkowski-Bouligand dimension Δ_{MB} used in [5] is defined as $\Delta_{\mathrm{MB}} = \lim_{\eta\to 0}[\ln N_\eta/\ln(1/\eta)]$, where N_η is the smallest number of disks of diameter η needed to cover the graph of the signal analyzed, plotted as a function of the time.

The surrogate data method [16] is applied below (Sec. III C) to show that the low values of correlation dimension of the BN signal cannot be treated as simple artifacts and therefore, supports the argument for determinism in the Barkhausen noise.

II. THE EXPERIMENT

The experimental setup to measure BN is shown in Fig. 1.

The nature of the experiment requires high precision measurements of tiny (microvolt) signals and this is the reason for using a very simple configuration with an open magnetic circuit and a single pick-up coil (no compensating coil).

Assuming that Barkhausen noise may exhibit a stochastic character due to defects and impurities it is expected that, in amorphous materials, Barkhausen domain wall jumps should be definitely more random than in any crystalline material. Therefore, when looking for a nonstochastic explanation of the physics of the effect, amorphous samples are more suitable than polycrystals where both the crystalline structure and the texture of the grain boundaries could accidentally mimic nonlinearities. Taking this into account the material chosen for the experiment was an amorphous $Fe_{80}B_{20}$ ribbon with the following dimensions: 40 mm long, 2.5 mm wide, and 30 μm thick. An amorphous ribbon with these dimensions is expected to have only a few domains, the walls of each are perpendicular to the plane of the ribbon [17].

The sample was driven by a sinusoidal magnetic field produced by two coaxial (Helmholtz) coils placed 12 mm from each other. This configuration was chosen empirically and for the small area of observation used it seemed to be more suitable and convenient [18] than using a solenoid. As the observed material was magnetically soft, a standard laboratory wave form generator afforded the magnetic saturation of the sample. The pick-up coil—empirically selected—was a very low-capacity radio coil having the inductance $L = 2.45$ mH, impedance $R = 28.4\ \Omega$, and dimensions 10 mm wide, 6 mm inner and 15 mm outer diameter. The sample was placed inside the pick-up coil.

The voltage signal (proportional to dB/dt) induced on the pick-up coil was amplified by a low noise, battery operated, two stage amplifier, custom designed for transmitting low level pulses with a high rate. To minimize the deformations of the wave front of the induced signal the first stage of the amplifier was built on a transistor while the second stage was a low-noise video integrated circuit amplifier. The parameters of the amplifier were as follows: amplification 700 times and frequency range 100 Hz–0.7 MHz. The noise of the measuring equipment was on the level of 5 mV at 0.5 V of the output signal. The amplifier together with the coils and the sample were magnetically screened by three coats of soft iron.

The Barkhausen noise signal was registered by a 12-bit A/D card (KIETHLEY-DAS 58) allowing to record up to 1×10^6 sample points measured with sampling frequencies up to 1 MHz. Data acquisition and the analysis were done with the help of a PC computer.

Since the Barkhausen effect is observed only for fields close to the coercive point, as the sample is magnetized along the hysteresis loop, BN is seen as characteristic ''packets'' of noise superimposed on the driving wave form. In fact, here the driving component was filtered out through a simple RC passive filter (relaxation time $\tau = 2$ ms) so that the only signal recorded was the medium and high frequency Barkhausen noise. Several packets of the Barkhausen noise measured in this way are shown in Fig. 2. For each period of the driving field two packets of BN were observed. Consequently, alternating packets corresponding to opposite phases of the driving field were obtained. Because of the symmetry of the driving signal there should be no difference between those groups of packets. Nevertheless, the irreversibility of the magnetization process cycle can break the symmetry so, for further analysis, only fragments with the same drive field phase were taken.

The above method of measurement gives the possibility to obtain a sequence of samples of the noise that can be considered as measured in identical experimental conditions. This allows the application of statistical methods to the data.

The data were obtained with sampling frequencies from 100 kHz to 1 MHz. The frequency of the driving field was varied from 0.5 to 50 Hz and several values of the amplitude

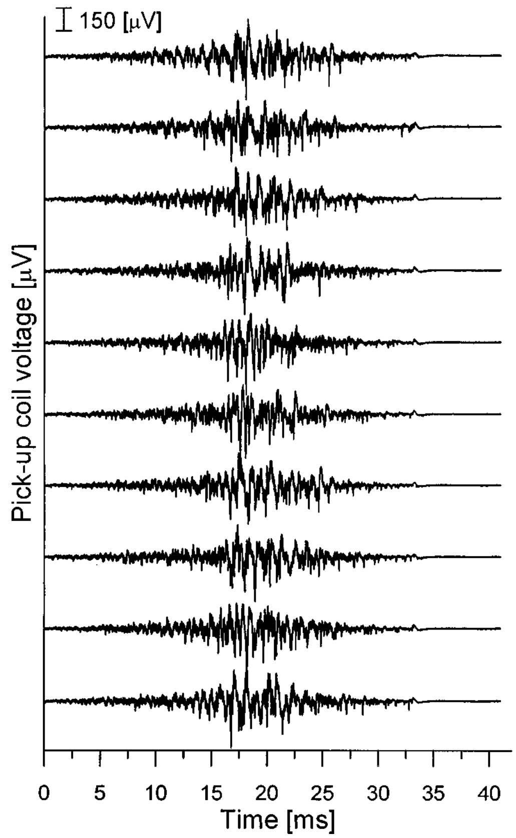

FIG. 2. Barkhausen noise measured in the experiment. The packets of BN are extracted from the same time series and are in the same phase in relation to the driving wave form.

were applied. Both the amplitude and the frequency of the field influenced the level and the quality of the signal measured so, finally, the frequency 10 Hz and the amplitude of 10 V were chosen as conditions for the experiment. These conditions gave a high level of the Barkhausen noise signal in comparison with both the white apparatus noise and the low frequency signal coming from the driving wave form. The sampling frequency was set to 200 kHz so that, with 1×10^6 sample points, 50 periods of the driving wave form were recorded and 100 packets of BN signal were obtained, each of them having an effective length of about 8000 points (40 ms). The packets were separated by about 10 ms (2000 points) during which no signal was seen. These fragments were related to the saturated state of the sample or to the processes that were so slow that they did not give Barkhausen pulses. The left sides of the BN signal packets (see Fig. 2) represent the departure from saturated states and the creations of domain structures. The right sides are related to the annihilations of domain boundaries and the attainment of saturated states at the opposite side of the hysteresis loop. The middle parts of the packets exhibit large pulses due to the fully developed domain structure.

Comparing the above method of Barkhausen noise measurement with the methods used by some other authors two main differences should be pointed out. The first is that, here, the driving field was changed distinctively faster (compared to [5–7] but consistent with [11–13]) and this resulted in a stronger output signal, therefore the amplification required could be smaller although the frequency range of the amplifier had to be much wider. The second difference was that the driving field had a sinusoidal form and together with the low frequency component of the measured signal, it was filtered out at the input of the amplifier. In fact, what was observed here was only the medium and high frequency component of the induced signal. At a high rate of the driving field, the output signal has no longer the shape of separated individual Barkhausen pulses and is more similar to an avalanchelike phenomenon with overlapping events. The shape of a single BN packet shows some self-similarity in the sense of the occurrence of characteristic patterns in different scales but also a mutual similarity between different packets can be easily seen.

III. BARKHAUSEN SIGNAL PROCESSING

The analysis of the data consisted of power spectra and correlation dimension calculations.

A. Power spectra analysis

The power spectra were calculated using the standard fast Fourier transform (FFT) algorithm [19] for 8192 data points. In general, the power spectra of a finite time series calculated by means of the FFT algorithm are often deformed due to the convolution of the transform of the signal and of the rectangular time window. The problem is usually solved by forming the data into the shape of a window with both edges decreasing to zero. As the amplitude of the signal of the BN packets seen in Fig. 2 tapers off at both ends and forms a naturally windowed shape, no additional windowing was performed. Figure 3 shows an example of the power spectra for a single BN packet (a) and the average over the spectra of 50 BN packets (b). In the case of the averaged spectra the $1/f^{\alpha}$ behavior is well visible with $\alpha\approx0.9$. The slopes of the spectra were obtained by a linear fit of the chosen fragments of the log-log plot. A weak dependence of the slope α on the amplitude of the driving field was found and the results are depicted in Fig. 9(c).

B. Correlation integrals and correlation dimension

The correlation dimension calculation method was proposed in 1983 by Grassberger and Procaccia [20]. The authors used the delay coordinate reconstruction of the attractor from a time series due to Takens [21]. Consider a sequence of N points of a sampled (generated, iterated, etc.) signal:

$$\{x\}=\{x(0),x(\tau),x(2\tau),\ldots,x(i\tau),\ldots\},\quad i=0,1,\ldots,N-1. \tag{1}$$

From such a time series we can construct an m-dimensional space using the vectors

$$\vec{x}_i=(x_i,x_{i+L\tau},x_{i+2L\tau},\ldots,x_{i+(m-1)L\tau}), \tag{2}$$

where L is a constant determining the time lag in the reconstruction and m is the dimension of the reconstructed space (the embedding dimension).

The correlation integrals for the vectors (2) are defined as follows [20]:

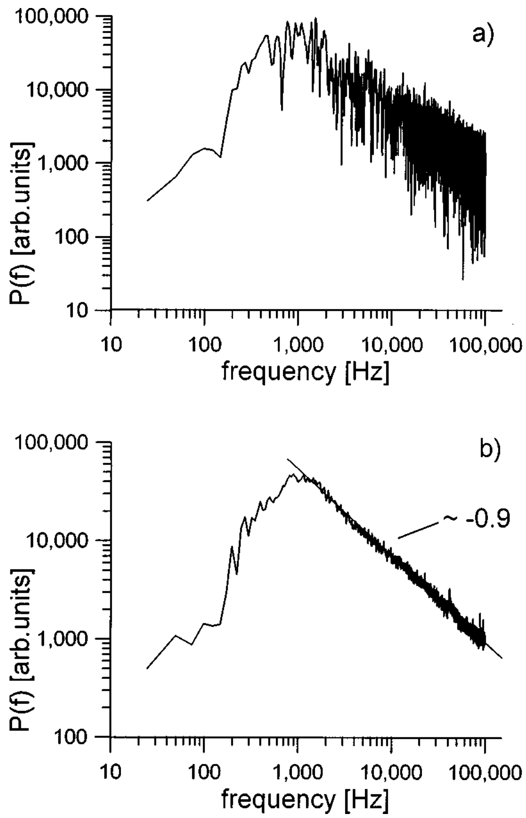

FIG. 3. (a) Power spectrum of a single packet of the Barkhausen noise. (b) Average power spectrum obtained by averaging the spectra of 50 BN packets. The spectra yield the slope $\alpha \sim 0.9$.

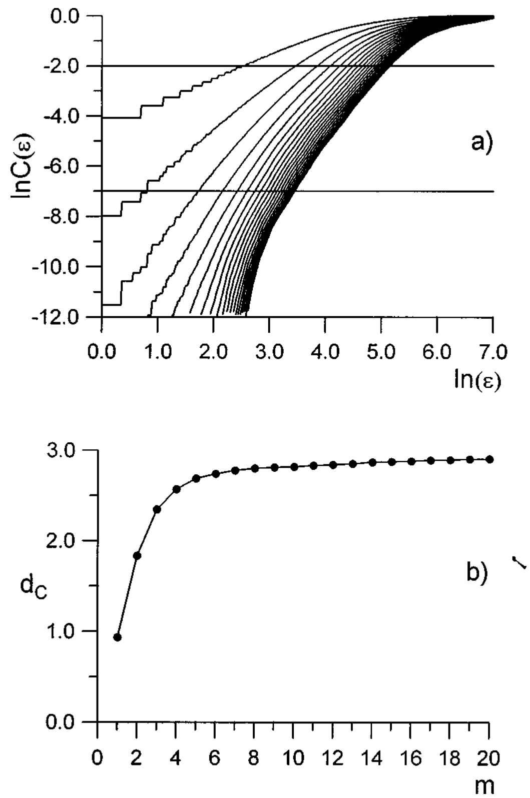

FIG. 4. (a) Correlation integrals for a sample BN packet for the embedding dimension varied (from the top) from 1 to 20. (b) The correlation dimension as the saturation of the values of slopes of the curves.

$$C(\varepsilon)=\lim_{N\to\infty}\frac{2}{N(N-1)}\sum_{j=1}^{N}\sum_{i=j+1}^{N}\Theta(\varepsilon-|\vec{x}_i-\vec{x}_j|), \quad (3)$$

where $\Theta(x)$ is the Heaviside function.

The correlation dimension d_c is then defined as

$$d_c=\lim_{\varepsilon\to 0}\frac{\ln C(\varepsilon)}{\ln(\varepsilon)}. \quad (4)$$

In practice [22], to decrease the linear correlations between neighboring points the summing in Eq. (3) is limited to $|i-j|>T$, where T is small. The proper choice of the parameter T improves the linearity of the correlation integrals.

The definition (3)–(4) is impractical in the case of experimental data that are often too short to estimate the limit $N\to\infty$. Also the limit $\varepsilon\to 0$ is unobtainable due to noise, inaccuracy or finite resolution of the experimental data. Therefore the definition is replaced by

$$d_c=\frac{\Delta\ \ln C(\varepsilon)}{\Delta\ \ln\varepsilon} \quad (4')$$

so that d_c is the value of the slope of $C(\varepsilon)$ in the range of its linear behavior.

The correlation integrals are calculated for m changing from 1 to some $m_{\max}$ and in the case of deterministic chaotic data are expected to saturate with m for

$$m\geqslant 2d_c+1. \quad (5)$$

In this work, the statistics $C(\varepsilon)$ were performed for 500 values of ε and they form an exponentially increasing sequence. This assures a uniform distribution of points in the logarithmic scale. The correlation integrals for a single BN packet for m varying from 1 to 20 are shown in Fig. 4. The number of points taken for the calculations was $N=6000$. The reconstruction was performed for the points taken from the central part of the packet (starting from the point 1000) and discarding identical lengths of data at both ends. The scaling areas of $C(\varepsilon)$ marked by horizontal lines on the plot give a good saturation of d_c and rule (5) is fulfilled well.

In order to find good scaling regions on the $C(\varepsilon)$ curves and also to choose the values of the parameters L and T additional calculations were made. Figure 5 (curves I) shows the variability of the correlation integrals with L changed from 1 to 58 and with the embedding dimension m held constant. The curves II and III in the graph correspond to the shuffled and phase randomized data (explained further in the text). The results of a similar procedure are seen in Fig. 6 but, there, the parameter changed is T. In both cases one can observe regions (nearly the same) where correlation integrals seem to be independent of the parameters varied and these common regions were chosen for determining d_c. The tuning of parameters L and T requires the choice of the curves $C(\varepsilon)$ of the best quality (the least deviation from linearity at small ε). Of course, while plotting curves with varying L, one should know the proper value of T and vice versa, so the

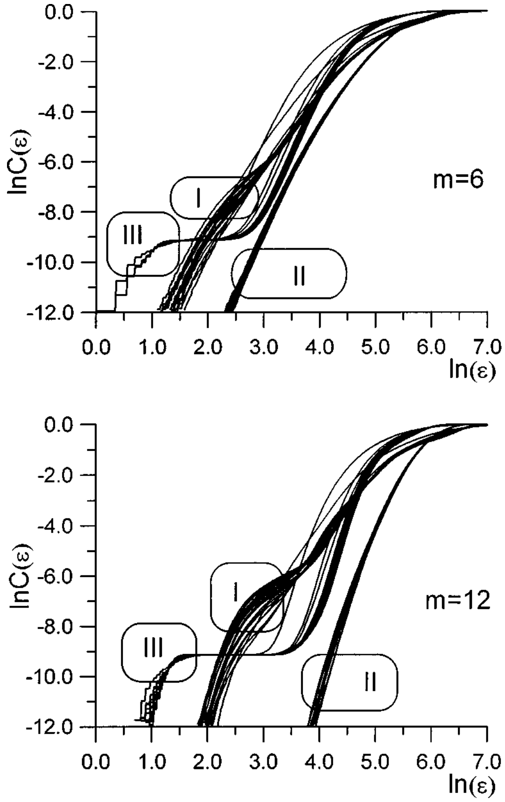

FIG. 5. Correlation integrals for a single Barkhausen noise packet calculated with the same parameters except for L that assumes the values (from the top, in each figure): 1,4,7$\cdots$58, respectively. Plots for two values of the embedding dimension $m=6$ and $m=12$ are shown for comparison. Curves I, II, and III correspond to the original, shuffled and phase randomized data, respectively.

best results were seen after a few iteration steps of the above procedure. By this method, the values of the parameters $L=4$ and $T=40$ were chosen.

Another method of estimating the proper value of L, based on the properties of the autocorrelation function [23] was also tested. It suggested values of the lag about twice higher. However, the use of such a lag resulted in a strong deformation of the correlation integrals for large m. On the other hand, we found that the slope of the $C(\varepsilon)$ curve changed significantly only for lags larger than 20.

To make sure that the number of points used for the reconstruction is not too small, calculations with $N=1500$, $N=3000$, and $N=28\,000$ were also performed. In the two first cases data sets were obtained by taking every fourth and every second point from the same area, respectively. To obtain the 28 000 points mutually corresponding fragments of five packets were composed into a single time series. In every case the values of d_c were very close but the quality of the scaling areas of $C(\varepsilon)$ and the saturation of d_c were somewhat worse at lower N values.

As the BN signal is strongly nonstationary, the value of d_c calculated here should be treated as some average. The relatively good quality of d_c obtained for small data sets prompted us to use a time window. Calculations with the use of sweeping time windows were performed and it was found that the correlation dimension is not constant for any fragment of a BN packet. In general, the correlation dimension on the left side of a packet is higher than that obtained on the

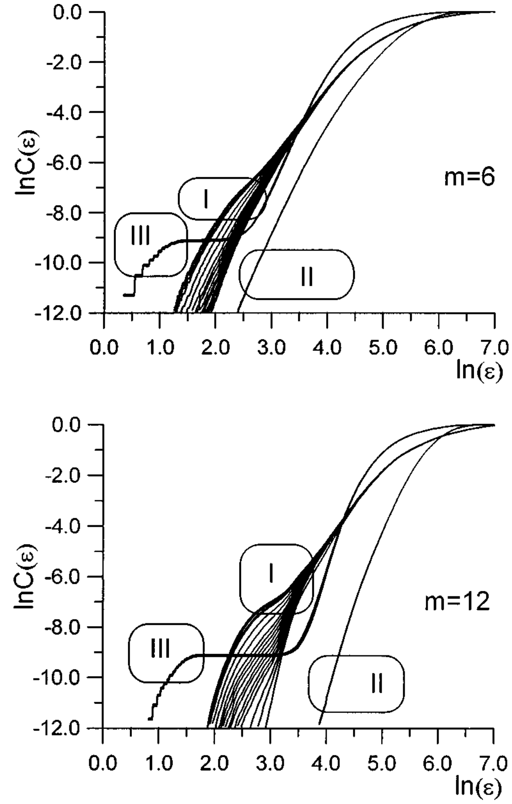

FIG. 6. The same as in Fig. 5. Here the only parameter changed is T, which assumes the values 1, 2, 4, 8, 10, 20, 30, 40, 45, 50, 55, 60, 65, 70, 75, 80, 90, 100, and 200, respectively.

right side but the overall behavior of the d_c is rather complicated. The results for the sweeping time window are depicted in Fig. 7. The time window of length $N=3000$ points was shifted with increments equal 400 points, and the time series analyzed included several packets of the BN. Here the slopes of $C(\varepsilon)$ calculated for m from 1 to 20 are plotted as functions of the position of the center of the time window. The areas where the plots are close to each other (i.e., where a good saturation with m occurs) and having a low value of the estimation error [indicating a good scaling of $C(\varepsilon)$] may be considered as characterized by well determined values of the correlation dimension. The other fragments (especially the spaces between packets) should be treated as stochastic.

The asymmetry of the signal can also be seen in the shapes of the packets. Its left sides seem to contain more small variations of the signal and have more complicated structures than the right edges, where the transitions to the saturated state are faster and more visible. This suggests that the transition from the saturated to the not saturated state may be more complex than the transition in the opposite direction. A relevant discussion considering the existence of the nuclei of the domain walls as crucial for the reproducibility of BN patterns may be found in [13]. The authors suggest that the features of domain wall motion remain deterministic as long as there is no nucleation or annihilation processes. In our experiment both phases are present at each magnetization reversal. From the observations here, it appears that the process of domain nucleation is more random than that of annihilation. This is borne out by the poor quality of scaling of the correlation integrals at this phase and by

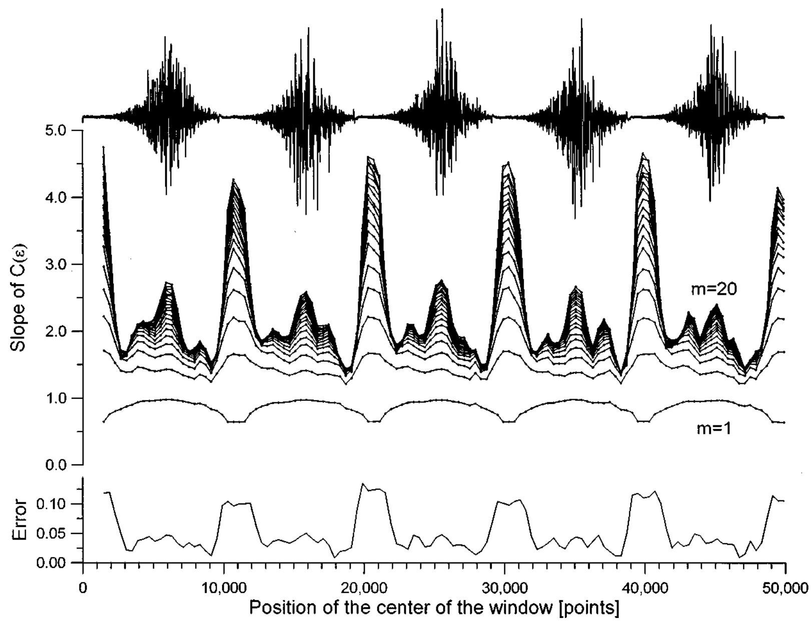

FIG. 7. The results of the calculation of correlation dimension using a time window with length $N=3000$ points, shifted with increments equal to 400 points. The corresponding BN signal is shown above. The errors are estimated as the error of slope calculation for maximal m.

the corresponding lack of saturation of the correlation dimension itself. The creation of domains may be dependent on the amorphous structure of the material but after the domains are created they seem to evolve deterministically.

A comparison of the correlation integrals for different packets of the BN signal was made. Figure 8 depicts the $C(\varepsilon)$ curves calculated for the same embedding dimension and with the same parameters N, L, and T but for the data from first 20 BN packets. No systematic differences can be seen between the curves, so they can be treated as fluctuations of some stable solution. Therefore, using the common scaling areas (chosen as described above) of all 50 packets with dimensions m from 1 to 20 the average slopes were calculated and the average value of the dimension: $\langle d_c \rangle$ was specified [Fig. 9(a)]. Here the error bars can be easily introduced as the standard deviations of the slopes of the curves. The histograms of $C(\varepsilon)$ slopes for different m are shown in Fig. 9(b). A somewhat worse saturation of $\langle d_c \rangle$ than in the case of calculations for a single BN packet may be explained by the fact that there is a group of BN packets that exhibit worse saturation of d_c with m. This group is well visible in histograms for high m.

The measure $\langle d_c \rangle$ described above was used to analyze BN signals obtained with different values of the amplitude of the driving wave form. The results are shown in Fig. 9(c) and are compared with the values of slopes of the averaged power spectra. For the lower values of the amplitude, it was difficult to estimate $\langle d_c \rangle$ because the linearity of $C(\varepsilon)$ curves was poor and the saturation of d_c was hardly seen. This suggests that the signal obtained with low sweep rate is more stochastic. A similar conclusion has been found in [15].

Another way of estimating the value of d_c as a global measure is a reconstruction considering many BN packets in one calculating procedure. For this purpose the vectors (2) were replaced by

$$\vec{x}_i=(x_i^1,x_i^2,\ldots,x_i^k,\ldots), \tag{6}$$

where $k=1,\ldots,m$ is the index of a BN packet.

This kind of reconstruction can be interpreted as a case of (2) but with L equal to the period of the driving field (here about 20 000 points). The results (Fig. 10) are again consis-

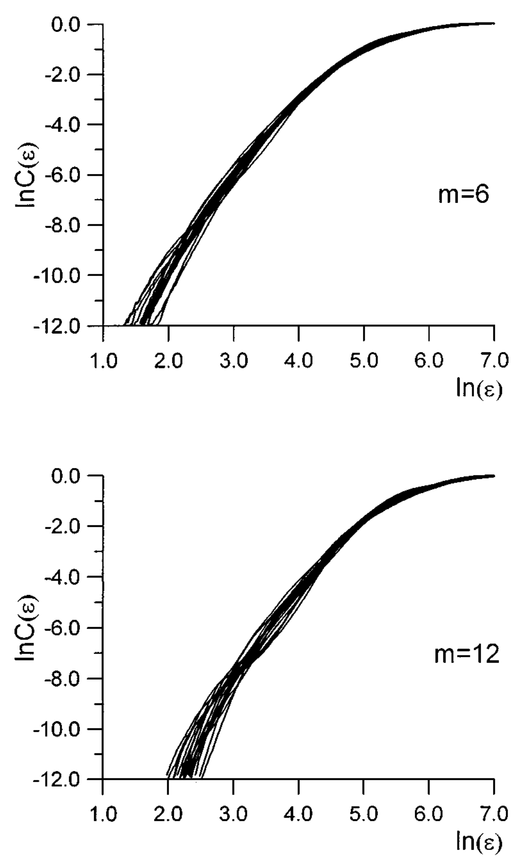

FIG. 8. Correlation integrals calculated for 20 different packets of the Barkhausen noise. The calculations were performed with the same parameters for each curve: $L=4$, $T=40$, $N=6000$. For comparison, the results for two values of embedding dimension $m=6$ and $m=12$ are shown.

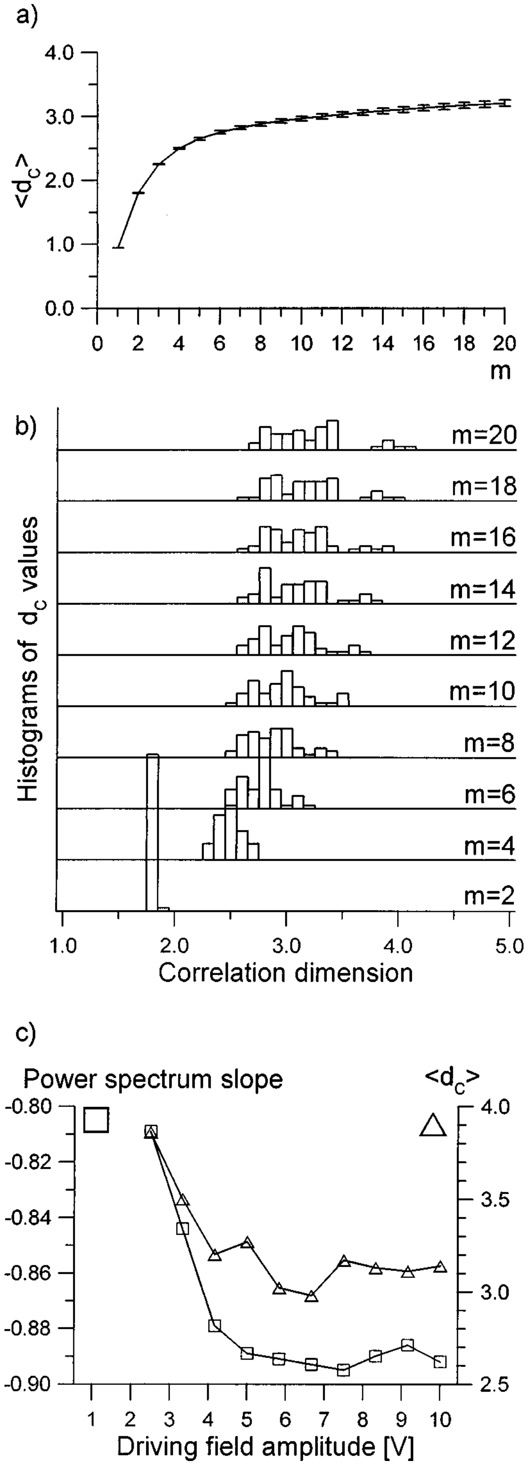

FIG. 9. (a) Correlation dimension $\langle d_c \rangle$ obtained by averaging the slopes of $C(\varepsilon)$ (see text for details). For each embedding dimension the slopes of 50 curves were averaged. (b) Histograms of the values of $C(\varepsilon)$ slopes for different embeddings. (c) Dependence of $\langle d_c \rangle$ and power spectra slopes on the amplitude of the driving field.

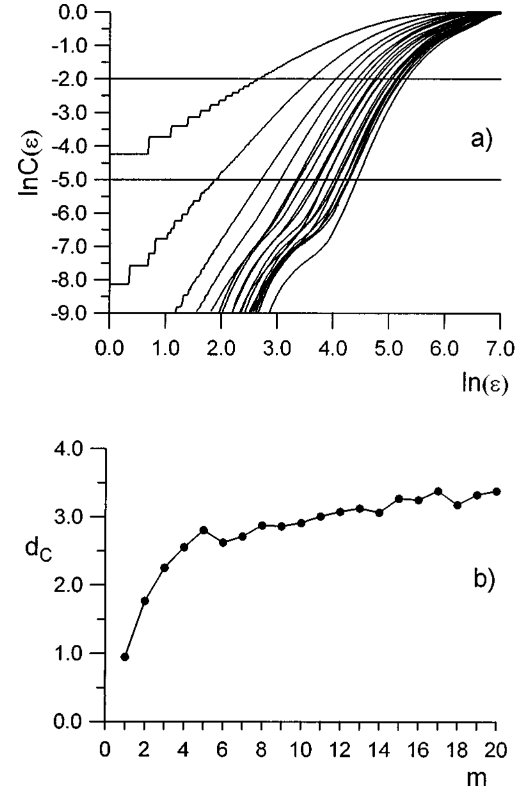

FIG. 10. The same as Fig. 4 but for the globally reconstructed attractor. Here the reconstruction vectors used are defined by Eq. (6).

tent with the values of d_c for a single packet using the standard delay reconstruction.

In spite of the presumably stochastic domain nucleation phase of each BN packet, the above embedding technique indicates that the nucleation process mainly defines the initial condition. The correlation dimension for the global embedding was very close to the average obtained for the BN packets. We also obtained only a small scatter between correlation dimension values for different packets. Given the relatively small number of data points used to calculate the correlation dimension, these are strong indications that the trajectory of each BN packet of the system follows the same attractor. The opposite and quite conceivable situation would be if the full saturation of the sample at one of the BN packet and the domain nucleation at the beginning of the next one changed the dynamical state of the system. Then, however, one would expect a different value of the correlation dimension at each magnetization reversal cycle, which is not the case here.

C. Surrogate data

In 1992 Theiler *et al.* proposed a statistical approach for identifying nonlinearity [16] in a time series. The first step is the preparation of surrogate data (SUR) sets that preserve specific properties of the original (experimental) data with other parameters randomly changed. The same method of data analysis should then be applied for the original and the surrogate data sets. If the difference in the results is significant, it means that the chosen method of analysis is sensitive enough to distinguish original data set from its surrogates. Otherwise, the result for the original data set should be treated as artificial and, therefore, should be rejected. A special case of surrogate data method is testing for determinism. It has been shown [24] that stochastic systems with power-law spectra may mimic deterministically chaotic behavior because their correlation integrals show scaling with ε and a

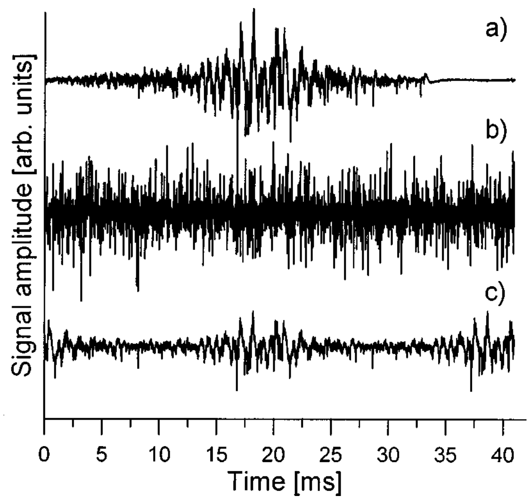

FIG. 11. Surrogate data sets: shuffled (b) and phase randomized (c) compared with the original data set (a).

saturation of the correlation dimension is seen. The SUR method applied in such case leads to the rejection of such a result as an artifact.

In our work, the surrogate data method was used for the measured Barkhausen noise in the context of the estimation of correlation dimension. Two surrogate sets were produced. The original signal was first randomly shuffled, so that its probability distribution (mean and variance of the original data), was preserved, with the frequency distribution and correlations randomized. The second surrogate set was obtained by a phase randomization of the original data. A BN packet was transformed by the FFT algorithm, and the amplitudes A_n and B_n corresponding to sine and cosine components of the transformation were obtained. Then the amplitudes were replaced by $A_n'=\sqrt{A_n^2+B_n^2}\,\sin\varphi$ and $B_n'=\sqrt{A_n^2+B_n^2}\,\cos\varphi$ where φ is a random phase. By using the inverse FFT procedure, the surrogate data set was obtained. In this case the preserved parameter was the Fourier spectrum but the probability distribution was changed. The surrogate data sets are shown in Fig. 11 in comparison with the original BN packet. It can be seen that phase randomized data (curve c) retains some of the original data (curve a) while the shuffled set (curve b) is much more different. For both SUR sets the correlation integrals were calculated in the same way as for the measured Barkhausen noise. The tuning of the parameters L and T was performed in the same way as for all BN packets, but now the slopes of the $C(\varepsilon)$ curve seemed to be weekly dependent on these parameters (see Figs. 5 and 6). Therefore the calculations of the correlation dimension for the surrogates were made with the same parameters as for the BN data. The results (Fig. 12) for both cases of surrogate data differ significantly from the results of the original data. No saturation of d_c is seen, so both ways of data randomization were detected by the method used. We may conclude that both SUR sets have lost the nonlinear properties of the Barkhausen noise signal. Of course this result cannot be treated as a rigorous proof of the determinism of Barkhausen noise but the necessary condition has been fulfilled.

Looking for sources of artifacts we also produced surrogate data sets in the form of random signals modeled in such a way as to obtain a visual similarity with the original BN packets but they also did not lead to any scaling behavior.

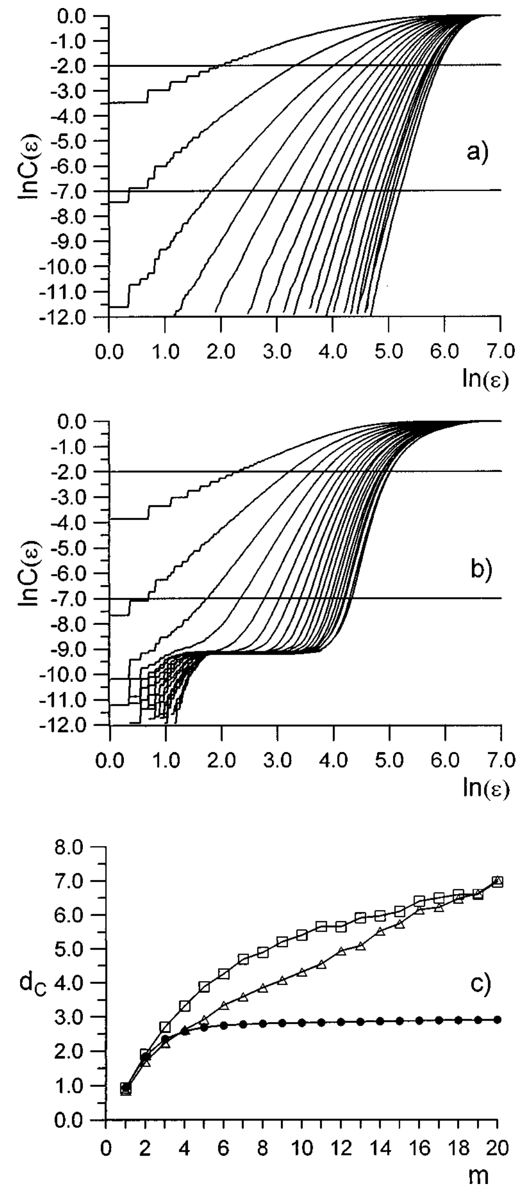

FIG. 12. Correlation integrals for surrogate data sets (a) shuffled and (b) phase randomized. (c) The same as Fig. 4(b) (dots) compared with the results for shuffled data (triangles) and phase randomized data (squares).

IV. DISCUSSION

We have proposed a method of analysis of the Barkhausen noise measured in an amorphous ribbon. The measurement method differs from the methods usually used (cf. [5–7]) because we have chosen a higher frequency of the driving field and we have centered our attention on the medium and high frequency parts of the signal obtained. Another new feature was the long-time observation of the magnetization processes. By increasing the measurement time to many periods of the driving field, we could apply a statistical approach to the signal that is locally nonstationary: we could compare different fragments of the signal having the same phase of the driving wave form. This approach implies a kind of stationarity that cannot be found in a signal coming from a single cycle of magnetization reversal. Although each individual packet of the BN signal represents a nonstationary process, by repeating the magnetization reversal many times we obtained a signal that may be treated as stationary. This is borne out by our numerical experiments described above, in which we computed the correlation dimension of a time series constructed of 28 000 data points extracted from several consecutive packets. The value of d_c obtained in this way was very close to that obtained for the individual packets and the quality of the calculation was not inhibited by this procedure.

The analysis method was based on the calculation of the correlation dimension, which is one of the fractal measures. However, the values of the dimension obtained in the present work should not be compared with the results of other research [5,15] because they used specific definitions that always lead to low values of fractal dimensions.

The scaling behavior of $C(\varepsilon)$ and the saturation of d_c with increasing embedding dimensions reflects low dimensionality. The results are similar for many BN packets and the statistics on the slopes of the $C(\varepsilon)$ curves were calculated to obtain an estimation of the average value of the correlation dimension. The low value of d_c leads to the conclusion that the observed Barkhausen effect contains or is caused by a deterministic process. The surrogate data test does not imply the rejection of this hypothesis. Moreover, the effect of determinism observed in this experiment was shown not to be an artifact due to a limited number of data points.

We propose that the low dimensionality of observed BN signal can be explained by the fact that there are only a few domain walls in the area of activity of the pickup coil. The domain walls move only in the plane of the ribbon and the walls interact through long range magnetostatic forces. Thus the number of degrees of freedom of the whole domain structure is limited and this results in the low value of the correlation dimension. The spread of the values of the correlation dimension obtained [see Fig. 9(b)] may be explained as being the result of the sensitivity of the domain nucleation process to initial conditions: each domain nucleation occurring at the beginning of each packet results in a different domain structure. On the other hand, two results should be considered together: (a) the value of the correlation dimension obtained from the global embedding [Eq. (6)] is consistent with that of the individual BN packets, and (b) a 28 000 point time series formed of five consecutive packets yields also a correlation dimension very close to the values obtained for individual packets. Both results indicate that a BN attractor exists: the domain nucleation process produces different initial conditions but the dynamical state of the system remains the same from one magnetization reversal to the next. Our conclusion goes beyond the results found in [11–13] where reproducibility of the BN signal was found for slow sweeping through a minor hysteresis loop. In our case, the experiment encompasses the domain annihilation phase. Furthermore, the argument of reproducibility given in [11–13] mainly concern the largest features of the measured signal. The correlation dimension, on the other hand, is extremely sensitive to minor details of the signal as a function of time. Reproducibility of the correlation dimension can be thus considered as a direct indication of the reproducibility of the dynamics of the BN process.

Finally, we note that the amplitude of the BN signal is maximal for the middle part of the hysteresis loop (i.e., the central parts of the packets) and tapers off at the saturated states. For such a specific shape of the signal the obtained value of d_c should be treated as a certain average value. We have performed an observation of the packets of BN with sweeping time windows. The results indicate that the values of d_c obtained from different parts of the signal (different phases of the magnetization process) are different. This effect requires, however, very careful analysis due to very small data sets involved and will be the subject of a future paper.

ACKNOWLEDGMENTS

This research was supported by Warsaw University of Technology Grant No. 503/051/070/1. Discussions with Professor Andrzej Sukiennicki are gratefully acknowledged.

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