ELSEVIER
Journal of Magnetism and Magnetic Materials 242–245 (2002) 1085–1088
journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

On the power spectrum of magnetization noise

G. Durin[a,*], S. Zapperi[b]

[a] *Istituto Elettrotecnico Nazionale Galileo Ferraris and INFM, str. delle Cacce 91, I-10135 Torino, Italy*
[b] *INFM unità di Roma 1, Dipartimento di Fisica, Università "La Sapienza", P.le A. Moro 2, 00185 Roma, Italy*

Abstract

Understanding the power spectrum of the magnetization noise is a long standing problem. While the earlier work considered superposition of 'elementary' jumps, without reference to the underlying physics, recent approaches relate the properties of the noise with the critical dynamics of domain walls. In particular, a new derivation of the power spectrum exponent has been proposed for the random-field Ising model. We apply this approach to the experimental data, showing its validity and limitations.

Keywords: Barkhausen noise; Domain wall dynamics; Soft magnetic materials

After almost a century since its discovery in 1909, the magnetization noise produced by the intermittent motion of domain walls, i.e. the Barkhausen noise, still represents an intriguing scientific challenge from the theoretical point of view. Considering the long-time and vast production of experimental and theoretical papers of the past, it is quite surprising that only recently an exhaustive comprehension of the noise properties has been achieved. The introduction of methods of statistical mechanics, in fact, made possible a reliable description of the intrinsic complexity of magnetization processes. In particular, the power law exhibited by the Barkhausen signal amplitude together with the avalanche size and duration has been explained in terms of an underling critical point. Its true nature is still under debate, as two main different approaches have been proposed: the zero temperature random-field Ising model (RFIM) [1], where criticality is set by the amount of disorder, and interface model, where a domain wall moves through a disordered medium and criticality is due to the depinning transition of the wall [2–4]. Exploiting the effects of long-range dipolar magnetostatic fields and of domain wall elastic tension on the depinning transition, we have recently shown that two distinct universality classes exist with different critical exponents and cutoff scaling dependence on the demagnetizing factor due to sample geometry [4]. These results have been confirmed on two polycrystalline and amorphous sets of materials, supporting the domain wall theory for the Barkhausen effect.

Despite these significant results, a proper description of the shape of the power spectrum noise is still not available. Significantly, about 80% of the Barkhausen literature have been devoted to this problem. Earlier approaches considering a description of the power spectrum shape as a superposition of elementary independent events (see for instance Ref. [5,6]) appeared to be unrelated to any microscopic mechanism, thus not clarifying the true origin of the magnetization process. Even attempts to link the power spectral exponent to the critical exponent of size distribution by a simple scaling relation [7–9] appears to be quite unsatisfactory and not confirmed, in general, by experiments. Experimental noise in fact show a quite complex pattern: the high-frequency part often follows a power law with exponents between 1.5 and 2, even if cases have been reported where the power law extension is very limited and a more complex pattern results [10]. The low-frequency part displays a marked peak, those position strongly depends on the magnetization rate, and an f^{α} dependence at lower frequencies with $0.5<\alpha<1$. Such a complicated pattern does not actually reveal all the complexity of the underlying dynamics of Barkhausen avalanches. Considering the high-order moments of the signal, different frequency bands appear to be very

*Corresponding author.
E-mail address: durin@ien.it (G. Durin).

0304-8853/02/$ - see front matter
PII: S0304-8853(01)01077-0

strong coupled, so that also high-order power spectra display power law dependences [11,12]. In addition, time asymmetries of third-order voltage correlations are found in amorphous samples, showing as high-frequency events precede on average the low-frequency ones [11]. All these properties are not currently explained by any of the existing models.

A derivation of the power spectrum exponent from a scaling analysis, at least for some simple models, can help for a better comprehension of the avalanche dynamics. A decisive step in this direction has been performed recently by Kuntz and Sethna [13], who derived the power spectrum exponent using scaling analysis of avalanches and applied it to the zero temperature RFIM, correcting earlier theoretical estimations [7–9]. It is worth noting that their scaling relations are very general and independent of the particular model used: clearly, different values of the critical exponents give different results. In this paper, we apply this analysis to various sets of experimental data, confirming the general validity of this approach for simple cases, and showing where it must be improved for a better description of the results.

Let us consider some of the scaling relations of Ref. [13] useful to the data analysis. The key scaling relation connects the average avalanche size $\langle s(T)\rangle$ with its duration T, that is $\langle s(T)\rangle \sim T^{1/\sigma\nu z}$ where the exponents σ, ν and z are defined in Ref. [8]. When the exponent of the avalanche size distribution τ is < 2, as usually in experiments [4], the high-frequency tail of the power spectrum is calculated to scale with exponent $1/\sigma\nu z$. This central result is based on the existence of a couple of scaling relations regarding the avalanche shape. The first one states that the average avalanche shape should scale in a universal way, so that

$$V(T,t) = T^{1/\sigma\nu z-1} f_{\mathrm{shape}}(t/T), \qquad (1)$$

where V is the signal voltage, t is the time and $f_{\mathrm{shape}}(t/T)$ is a universal scaling function having the approximated shape of an inverted parabola for the RFIM. The second relation analyzes the fluctuations of avalanche sizes considering the probability $P(V|s)$ of the occurrence of voltage V inside an avalanche of size s. This probability scales as

$$P(V|s) = V^{-1} f_{\mathrm{voltage}}(V s^{\sigma\nu z-1}) \qquad (2)$$

where f_{voltage} is another universal scaling function. With relations 1 and 2, the power spectrum exponent is obtained calculating the time–time correlation function in the case of adiabatically increase of the applied field and of a *complete separation of avalanches in time*, thus avoiding any avalanche correlation. All these considerations will be helpful to understand the experimental results.

We consider two kinds of soft magnetic ribbons, belonging to different universality classes as pointed out in Ref. [4]. An as-cast $Fe_{64}Co_{21}B_{15}$ amorphous alloy (28 cm × 1 cm × 23 μm), measured under moderate tensile stress ($\sigma \sim 20$ MPa), and a polycristalline Fe–Si 7.8 wt% ribbon (30 cm × 0.5 cm × 60 μm) produced by plan flow casting having grains of average dimension of 25 μm. The amorphous ribbon follows the universality class where the surface tension of the wall dominates the domain dynamics (short-range class), where $1/\sigma\nu z \sim 1.77$ [4]. Fig. 1 shows the comparison of the power spectrum with the average size distribution $\langle s(1/T)\rangle$ as a function of the inverse of avalanche durations. The agreement with the theoretical prediction is fairly good over an extended time range: at high avalanche durations (small frequencies), the time correlation between avalanches becomes relevant and the theoretical analysis is no longer valid. The inset of Fig. 1 show the same comparison in the case of the FeSi sample. This material falls in the universality class where long-range magnetostatic fields dominates the domain dynamics, giving $1/\sigma\nu z \sim 2$ [3]. Also in this case, the agreement is fairly good, but for a smaller high-frequency range. The precise reason for this fact is not clear, even though a visual inspection of the time signals of both materials can justify this result: in the amorphous alloy, the avalanches are well separated in time (see Ref. [14]), while in the FeSi alloy the separation is much less defined (see Ref. [15]). This is also confirmed by the fact that only in the latter material the critical exponents of size and duration distributions strongly depend on the applied field rate. This means that avalanche correlations, and thus time–time correlations, are significantly

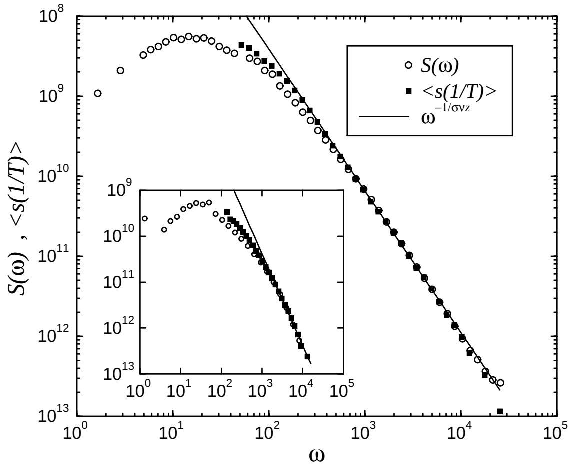

Fig. 1. Comparison of the power spectrum $S(\omega)$ with the average avalanche size $\langle s(1/T)\rangle$ as a function of inverse of avalanche duration T for an $Fe_{64}Co_{21}B_{15}$ amorphous ribbon and an FeSi 7.8 wt% polycrystalline alloy (inset). The theoretical prediction of Ref. [13] is also shown, with $1/\sigma\nu z$ equal to 1.77 and 2, respectively, as given by the interface model [4].

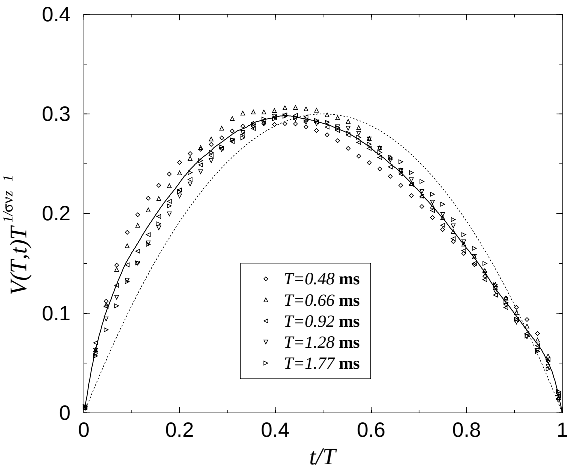

Fig. 2. Average avalanche shape (Eq. (1)) for the $Fe_{64}Co_{21}B_{15}$ amorphous ribbon using the scaling exponent $1/\sigma\nu z$ equal to 1.77. The full line is the average of the curves and the dotted line is a symmetric parabola.

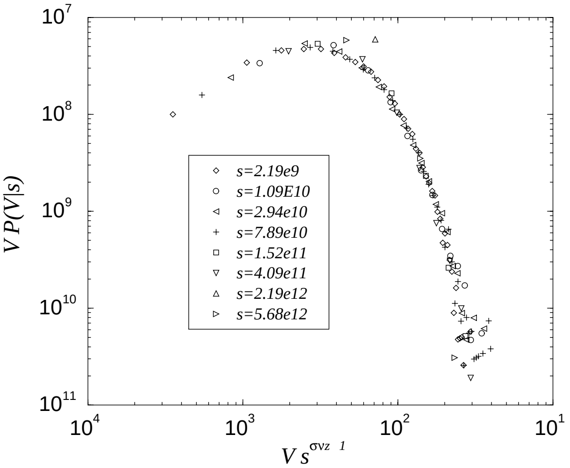

Fig. 3. Distribution of avalanche voltages at fixed voltage (Eq. (2)) for the $Fe_{64}Co_{21}B_{15}$ amorphous ribbon using the scaling exponent $1/\sigma\nu z$ equal to 1.77.

different, giving different spectral contributions. The results for the amorphous alloy are confirmed by the scaling of the average avalanche shape $V(T,t)$ (Fig. 2) and of the probability $P(V|s)$ (Fig. 3). In both figures, the theoretical value $1/\sigma\nu z \sim 1.77$ is used. Interestingly, the universal scaling function $f_{\rm shape}$ of Eq. (1) is not an inverted parabola as for the RFIM, but it shows a marked temporal asymmetry. This is compatible with the results of Ref. [11] concerning high-order spectra: the high- frequency signal components precede the low-frequency ones, so that an avalanche of a given size and duration starts with a fast signal ramp and relaxes at longer times. Interestingly enough, despite this time asymmetry, the predictions of Ref. [13] are confirmed, suggesting that the scaling properties are more important than the exact shapes of average avalanches. This conclusion strongly contradicts with the basic assumption often reported in the literature [5,6], where a distribution of 'elementary' avalanches with a *predefined* shape (often exponential) is summed up to calculate the power spectrum.

We must add that the avalanches of the FeSi alloy does not show such a nice scaling. In particular, short and long avalanches have markedly different shapes, as the former is approximately an inverted parabola, while the latter show a flat central region. Also the scaling of $P(V|s)$ is not perfectly compatible with the theoretical exponent $1/\sigma\nu z = 2$. All these features could explain the limited agreement between the power spectrum and $\langle s(T) \rangle$, and surely need a more extensive analysis, taking into account avalanche correlations and the dominant role of demagnetizing fields.

From the analysis of experimental results shown above, one may argue that materials belonging to the short-range class also exhibit power spectra scaling as $1/\sigma\nu z$. As a matter of fact, the application of larger applied tensile stresses on the amorphous material does not change the universality class [14], but reveals a more complex behavior. In particular, $S(1/\omega)$ and $\langle s(T) \rangle$ do no longer scale in a similar way at high stresses, even if $V(T,t)$ and $P(V,s)$ still rescale approximately with $1/\sigma\nu z = 1.77$. This behavior reflects the change of the avalanche shape as shown in Ref. [14]: the cutoff of avalanche duration decreases while keeping the size distribution invariant. As the scaling range of duration distribution gets shorter, we expect that the longest avalanches, close to the cutoff value, are increasingly more effective in the time–time correlation of the signal, and thus to the power spectra. Their frequency content is not obviously taken into account in the scaling calculations of Ref. [13].

As clearly shown above, many different aspects can enter in the definition of the scaling properties of the Barkhausen signal. As already pointed out [11,12], a more complex analysis is required to evaluate in detail the statistics of avalanches. In this respect, the analysis of Ref. [13] not only gives a new approach to the long standing problem of power spectra shape, but introduces precise statistical tools helpful both to the experimental analysis and to the theoretical description of magnetization processes. Within some limitations to be further investigated, the results described above are fully compatible with our interface models [2–4]. This is quite surprising, considering that this model considers the motion of a single domain wall with strong simplifications of the fields relevant to the dynamics (especially of magnetostatic fields). In fact, a real material typically shows a complex pattern of multiple domains with no easily predictable field configuration. Here temporal and spatial correlations are important, resulting in a very complex behavior of time–time correlation and thus of power spectra.

References

[1] J. Sethna, K. A. Dahmen, C. R. Myers, Nature 410 (2001) 242.
[2] P. Cizeau, S. Zapperi, G. Durin, H. E. Stanley, Phys. Rev. Lett. 79 (1997) 4669.
[3] S. Zapperi, P. Cizeau, G. Durin, H. E. Stanley, Phys. Rev. B 58 (1998) 6353.
[4] G. Durin, S. Zapperi, Phys. Rev. Lett. 84 (2000) 4075.
[5] P. Mazzetti, Nuovo Cimento 25 (1962) 1322.
[6] P. Arquès, J. de Phys. 29 (1968) 369.
[7] U. Lieneweg, W. Grosse-Nobis, Inter. J. Magn. 3 (1972) 11.
[8] K. Dahmen, J. P. Sethna, Phys. Rev. B 53 (1996) 14872.
[9] D. Spasojevic, S. Bukvic, S. Milosevic, H. E. Stanley, Phys. Rev. E 77 (1996) 2531.
[10] G. Durin, A. Magni, G. Bertotti, J. Magn. Magn. Mater. 160 (1996) 299.
[11] J. R. Petta, M. B. Weissman, G. Durin, Phys. Rev. E 57 (1998) 6363.
[12] J. R. Petta, M. B. Weissman, G. Durin, IEEE Trans. Magn. 34 (1998) 1171.
[13] M. C. Kuntz, J. P. Sethna, Phys. Rev. B 62 (2000) 11699.
[14] G. Durin, S. Zapperi, J. Appl. Phys. 85 (1999) 5196.
[15] G. Durin, A. Magni, G. Bertotti, Fractals 3 (1995) 351.