Determination of Barkhausen Signal Scaling From Higher Order Spectral Analysis

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Abstract—**Third and fourth order spectral measurements of Barkhausen noise in single crystal 3% Wt. Si-Fe and previously measured $Fe_{21}Co_{64}B_{15}$ samples showed striking differences. FeSi spectral measurements were consistent with independent pulse models, unlike data from amorphous $Fe_{21}Co_{64}B_{15}$. Our measurements indicate that the variability of the high frequency exponent, which experimentally ranges between 1.5 and 2, is due to effects upon domain structure and other material properties.**

IndexTerms—**Barkhausen effect, Barkhausen noise, domain wall dynamics, magnetization process**

I. Introduction

The Barkhausen effect has received renewed interest recently, partly due to claims that it may be an example of a system exhibiting self organized criticality [1]. The earliest theoretical works on Barkhausen noise arrived at the approximately $1/f^2$ experimental high frequency power spectrum exponent using independent pulses with suitable amplitude and time distributions [2]. In 1990, the group of Alessandro *et al.* (ABBM) created a somewhat more realistic theory for the Barkhausen effect [3], [4], where the motion of a domain wall can be described in terms of a single position moving at velocities which vary due to a spatially varying coercive field. This phenomenological single degree-of-freedom model actually ignores any microscopic detail of the (underlying) magnetization processes, while experimental data suggests that there are interactions between different domains and/or segments of domain wall [5], [6]. New microscopic theories have been recently developed to include effects of the domain wall curvature and of the local and overall demagnetizing fields [7], [8]. The model of Cizeau *et al.* leads to the ABBM equations for the motion of the average position of a domain wall in a fairly realistic limit. These equations provide surprisingly good fits to Barkhausen pulse amplitude, duration and size distributions in many different materials, showing a marked universality. However, the non-universality of the power spectrum remains unexplained [9]. Experimentally, the high frequency portion of the power spectrum falls off as $f^{-\beta}$ $(1.5 < \beta < 2)$, β varying with sample composition and annealing treatments. The ABBM model predicts β=2 while independent pulse models have not made successful statistical predictions of the type made by ABBM. Neither type of model has incorporated qualitative dependence of the high frequency regime on sample characteristics such as permeability or domain structure.

In this paper we discuss measurements of the frequency dependent third and fourth moments of the Barkhausen signal collected on single crystal 3% Wt. Si-Fe and show that the results can be analyzed in terms of an independent pulse model, in sharp contrast to data taken by similar methods on the amorphous $Fe_{21}Co_{64}B_{15}$ alloy [10]. The main question is whether the high frequency portion of the power spectrum is due to individual pulses of frequency f, equal to the inverse of the pulse duration τ, or from high frequency structure on much longer-duration pulses. A correlation between low frequency voltage and high frequency power would support the latter picture.

In order to study the third and fourth moments of the Barkhausen signal we perform a Haar transform on the voltage time series and then use $S_{1.5}[f_2,f_1]$ and $S_2[f_2,f_1]$, which have been previously defined [11], [12]. In general, $S_2[f_2,f_1]$ gives an indication of how the power at frequency f_1 fluctuates at frequency f_2. $S_{1.5}[f_2,f_1]$ describes the correlation between fluctuations at frequency f_2 in the power at frequency f_1 and fluctuations at f_2 in the voltage. These two tools allow tests, not possible with simple power spectra, of differences in domain dynamics between different materials. For example, a flat $S_2[f_2,f_1]$, which means that the fluctuations in the noise power at frequency f_1 themselves have a white spectrum, would be obtained in an independent pulse model. $S_{1.5}[f_2,f_1]$ as a function of f_2 indicates how the high frequency components in a voltage pulse of width $1/f_2$ fall off with frequency f_1.

II. Experiments

The experiments were performed on single crystal 3% Wt. Si-Fe. The FeSi dimensions were 19 cm x 0.9 cm x 0.2 mm. This sample geometry reduces the demagnetizing field. The domains are aligned along the long axis of the sample with roughly 5 domain walls. General experimental procedures have been described elsewhere [10].

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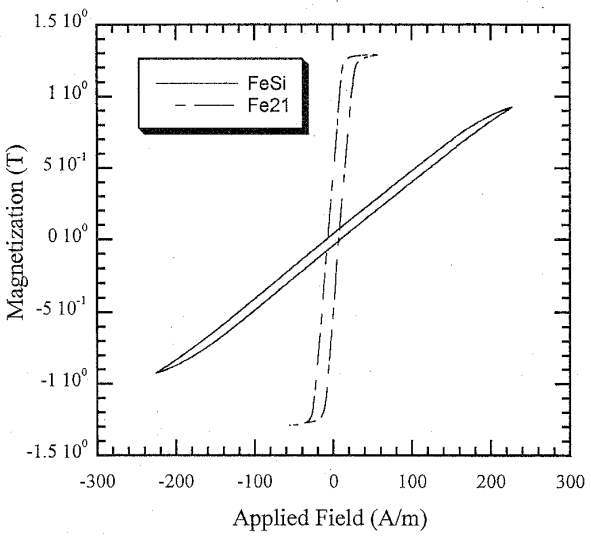

Fig. 1. Hysteresis loops for $Fe_{21}Co_{64}B_{15}$ and FeSi. The maximum applied field in the hysteresis loops correspond to the maximum applied field during the data acquisition.

All of the data in this article, except for the hysteresis loops, have been averaged over 350 sweeps, corresponding roughly to 85,000 Barkhausen events, with $S_{1.5}[f_2,f_1]$ being calculated only on the positive portion of the sweep. For clarity, $S_2[f_2,f_1]$ and $S_{1.5}[f_2,f_1]$ were smoothed using a Stineman function [13].

Fig. 1 shows the hysteresis loops for FeSi and a previously measured $Fe_{21}Co_{64}B_{15}$ sample, collected by integrating over the Barkhausen signal. Data were only acquired in the linear portion of the hysteresis loop. The $Fe_{21}Co_{64}B_{15}$ sample has a much more rectangular hysteresis loop than the FeSi.

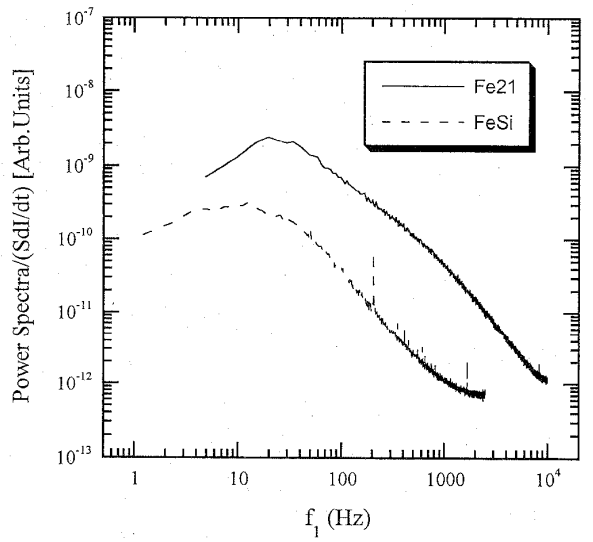

Fig. 2. Power spectra for $Fe_{21}Co_{64}B_{15}$ and FeSi, normalized by $S\dot{I}$. The $Fe_{21}Co_{64}B_{15}$ spectrum falls off as $f_1^{-1.2}$ near 100 Hz and as $f_1^{-1.9}$ above 1 kHz. The FeSi spectrum falls off roughly as $f_1^{-1.65}$ above 100 Hz.

III. Results

Fig. 2 shows the power spectra for FeSi and $Fe_{21}Co_{64}B_{15}$, normalized by $S\dot{I}$ where S is the sample cross section and $\dot{I}$ is the magnetization rate of change. The data were collected at driving frequencies of 0.03 Hz and 0.05 Hz for $Fe_{21}Co_{64}B_{15}$ and FeSi, respectively. The spectra resemble those previously measured on similar materials [14]. The ABBM model predicts a slope of f_1^{-2} for large f_1. Note the kink in the $Fe_{21}Co_{64}B_{15}$ spectra near 800 Hz.

Fig. 3 contains $S_2[f_2,f_1]$ and $S_{1.5}[f_2,f_1]$ for five f_1 as a function of f_2 for FeSi. $S_2[f_2,f_1]$ is nearly flat as a function of f_2 and falls off as $f_1^{-1.2}$ indicating that the majority of the power at f_1 comes from separate pulses which have time scales of approximately $1/f_1$. $S_{1.5}[f_2,f_1]$ is highly dependent on f_1, below 100 Hz, with an exponent of $f_1^{-0.9}$ at $f_2 = 40$ Hz, also indicating that the majority of the power at f_1 comes from pulses with duration $1/f_1$. The high frequency tail of $S_{1.5}[f_2,f_1]$ falls off as $f_2^{-1.7}$.

Fig. 4 contains $S_2[f_2,f_1]$ and $S_{1.5}[f_2,f_1]$ for five f_1 as a function of f_2 from a previously measured $Fe_{21}Co_{64}B_{15}$ sample. The second spectra fall of as $f_1^{-0.35}$ and $f_2^{-0.35}$ above 100 Hz. $S_{1.5}[f_2,f_1]$ falls off as $f_2^{-0.9}$ near $f_2 = 100$ Hz and as $f_1^{-1.5}$ above 1 kHz. This means that the variance in the high-frequency power does not come from independent short-duration pulses (which would give flat $S_2[f_2]$), but rather from events which cluster on time scales much longer than $1/f_1$. More detailed $Fe_{21}Co_{64}B_{15}$ data analysis can be found in Petta *et al.* [10].

IV. Discussion

Our data show that whether the form of the high frequency power spectrum is due to the structure of the individual Barkhausen pulses or the distribution of pulse

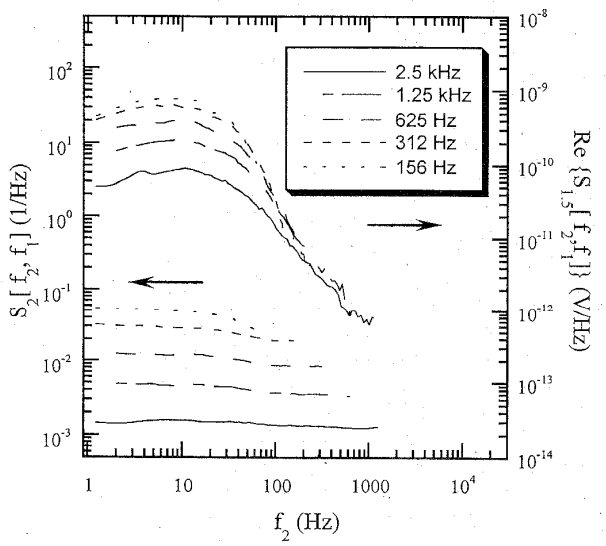

Fig. 3. $S_2[f_2,f_1]$ and $S_{1.5}[f_2,f_1]$ for five f_1 as a function of f_2 for FeSi. $S_{1.5}[f_2,f_1]$ fall off as $f_1^{-0.9}$ at $f_2 = 40$ Hz with a high frequency exponent of $f_2^{-1.7}$.

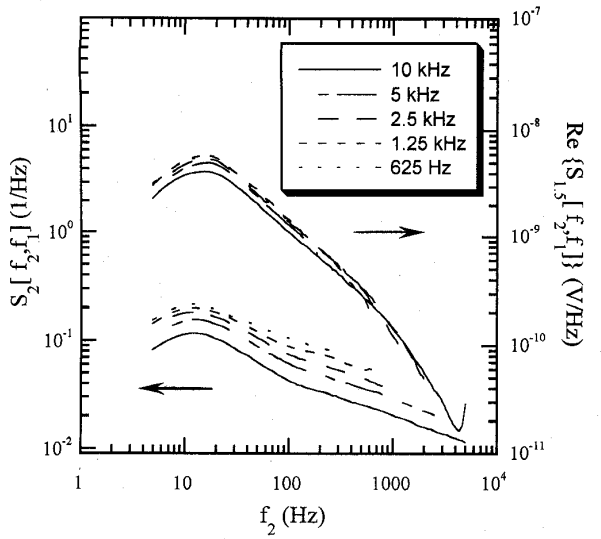

Fig. 4. $S_2[f_2,f_1]$ and $S_{1.5}[f_2,f_1]$ for five f_1 as a function of f_2 for $Fe_{21}Co_{64}B_{15}$. The $S_{1.5}[f_2,f_1]$ spectra fall off as $f_2^{-0.9}$ near $f_2 = 100$ Hz, with a high frequency exponent of $f_2^{-1.5}$. The $S_2[f_2,f_1]$ spectra fall off as $f_1^{-0.35}$ near 100 Hz, and as $f_2^{-0.35}$ above $f_2 = 100$Hz

widths varies from material to material. The clear dependence of $S_{1.5}[f_2,f_1]$ and $S_2[f_2,f_1]$ on f_1 in the FeSi system shows that most of the power in the high end of our observed frequency range is due to pulses with duration $1/f_1$. For FeSi it is possible to derive a relationship between the pulse height and duration [15]. We begin by assuming that the noise power contribution at frequency f_1 comes from pulses of duration (within a factor of 2) $\tau = f_1^{-1}$ and that the pulse height, h, obeys the power law $h \alpha f_1^{-g}$. Then the variance in the voltage, $f_1 S_1(f_1)$, is proportional to $n\tau h^2$, where n is the number of pulses per unit time. The second spectra, as a function of f_1, are inversely proportional to n. Near 100 Hz, $S_1(f_1) \alpha f_1^{-1.65}$ and $n \alpha f_1^{1.3}$. One then approximately obtains $h \alpha \tau^{0.47}$, a reasonable result. In the ABBM model, $g = 1$.

The behavior of the $Fe_{21}Co_{64}B_{15}$ alloy is very distinct from that of the FeSi system. The weak dependence of $S_{1.5}[f_2,f_1]$ on f_1 in $Fe_{21}Co_{64}B_{15}$ shows that most of the power in the high end of our observed frequency range actually comes from fine-structure on the same long pulses giving the low-frequency part of the spectrum. Attempting the calculation explained in the previous paragraph for $Fe_{21}Co_{64}B_{15}$ gives unrealistic results, e.g. pulse heights that are decreasing functions of width in the 1 kHz regime.

The fact that the FeSi higher-order spectra differ so much from the $Fe_{21}Co_{64}B_{15}$ spectra raises some interesting questions. Most schematic Barkhausen models ignore the specifics of material properties. An understanding of why the structure of the Barkhausen pulses varies so much from material to material requires comprehension of how sample properties such as permeability and domain structure affect the pinning field seen at a domain wall. It is not surprising that higher permeability material has more extended, complicated domain wall avalanches [16], but this complicted behavior may also be due to the larger number of active domain walls in $Fe_{21}Co_{64}B_{15}$. Thus a successful model must predict not only the distribution of the pulse widths but also the distribution of frequency components within single pulses.

We conclude that under the conditions of a typical Barkhausen experiment in soft metallic ferromagnets, a simple distributed-pulse parameter model only works approximately in some materials, but fails badly in others. More realistic Barkhausen theories must include effects due to domain wall configurations and other sample characteristics in order to explain the clear differences in the higher moments of the Barkhausen signal.

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