QUANTITATIVE ANALYSIS OF SURFACE BARKHAUSEN NOISE MEASUREMENTS

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ABSTRACT. Barkhausen noise is the result of abrupt magnetic domain activity around pinning sites in ferromagnetic materials. Our recent work has investigated permeability-independent measurements of Barkhausen noise, made possible by directly controlling the magnetic circuit flux and its derivative. This approach, as opposed to control of the excitation coil current used in many other studies, significantly reduces sensitivity to lift-off, improves on measurement reproducibility and also improves analysis capability. Here, quantitative measurement and analysis techniques that can be applied to the measured waveforms are demonstrated. These start with single Barkhausen events, and expand to all the measured events in a full sweep around the hysteresis loop. A set of non-redundant parameters, useful for the characterization and analysis of Barkhausen noise, is presented.

Keywords: Barkhausen Noise, Flux control, Ferromagnetic, Hysteresis, Pinning Sites
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INTRODUCTION

Barkhausen noise (BN) is the result of abrupt local changes of magnetization distribution (M) in ferromagnetic materials as the domain structure re-configures around pinning sites in response to an external magnetic field (H) [1,2]. BN is a candidate for nondestructive evaluation (NDE) applications due to its response to elastic stress [3].

Consistent BN requires that M be reproduced for each measurement. A general description of bulk magnetic behaviour in a material is:

\[ B = \mu_0 (H + M) = \mu_0 (1 + \chi_m)H = \mu_r \mu_0 H \]  \hspace{1cm} (1)

where \( B \) is the flux density distribution, \( \mu_0 \) is the permeability of free space, \( \chi_m \) is the susceptibility tensor, and \( \mu_r \) is the relative permeability tensor [2,4]. In ferromagnetic materials the \( \chi_m \) is typically much greater than unity, thus M has a much greater contribution to B than does H [1]:

\[ \chi_m \approx 1 \]  \hspace{1cm} (2a)

\[ B \approx \mu_0 M \]  \hspace{1cm} (2b)

While \( H, B \) and \( M \) are time-dependent vector distributions, measurements are simplified by assuming that in an excitation coil with \( N_{ac} \) turns, the average field \( \langle H \rangle \) is

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related to the current \( (I) \) in the coil by the mean length of the magnetic circuit \( (\ell) \) via [2]:

\[
<H> = \frac{N_m I}{\ell}
\]  

(3)

Similarly, the total flux \( (\Phi) \) in the circuit, which is a conserved quantity, is [2]:

\[
\Phi = \int \mathbf{B} \cdot d\mathbf{A}
\]

(4)

where \( A \) is the cross-sectional area of the circuit. Finally, using Faraday’s law of induction, the voltage \( (V_p) \) on a detection coil with \( N_F \) turns is [2]:

\[
V_p = -N_F \frac{d\Phi}{dt}
\]

(5)

In typical BN measurements an electromagnet is used to induce a magnetic flux in the sample under test, and a sensing coil is placed either in contact with or wound around the sample. While most apparatus control \( I \) in the electromagnet and hence \( H \), the surface Barkhausen noise (SBN) measurement technique described in this work controls \( \frac{d\Phi}{dt} \) directly, and therefore \( \Phi \) through integration with respect to time \( t \):

\[
\Phi(t) + \Phi_{REM} = \int_0^t \frac{d\Phi}{d\tau}(\tau) \, d\tau
\]

(6)

where \( \Phi_{REM} \) is the remnant flux in the circuit at \( t = 0 \).

Since \( \Phi \) is conserved in the circuit, controlling \( \Phi \) ensures that the average flux density distribution \( \langle B \rangle \) and hence the average magnetization distribution \( \langle M \rangle \) are reproduced, within the approximation described by equation 2. With both \( \Phi \) and \( \frac{d\Phi}{dt} \) known for every measurement, it is possible to relate the BN signal to these parameters, which can, in turn, be directly related to both the bulk domain configuration and the bulk rate of domain reconfiguration.

**DOMAIN THEORY**

Atomic dipole moments in ferromagnetic materials spontaneously align in groups called domains, which self-order to minimize the total magnetic energy in the material. In the Fe BCC lattice, domain magnetizations tend to be aligned with the \( \{1,0,0\} \), \( \{0,1,0\} \) and \( \{0,0,1\} \) crystallographic directions, which results in domains being oriented 90° or 180° with respect to each other [2].

The transition between one domain and its neighbor is called a domain wall, and has a finite width of about 100 atoms [2]. Domain wall formation requires energy, as the dipoles within the walls are not in the preferred orientation with respect to the lattice, nor parallel with their neighbors. Introducing elastic stresses or texture within a ferromagnetic material results in a preferential alignment of domains with the tensile strain or \( \{1,0,0\} \) texture axis, and an increase in the population of 180° domains in this orientation.

Energy is minimized in response to an external magnetic field by increasing the number of dipoles aligned with the applied field. In order for this energy minimization to occur domain walls move, domain orientations rotate, and domains are created and annihilated, resulting in an increase of the bulk magnetization of the material.
Features such as inclusions, grain boundaries, and dislocations provide local potentials that minimize the magnetic energy of the system. These features are called pinning sites, as they tend to halt the change in magnetization. When the applied field is sufficient to overcome the potential barrier, there is an abrupt change in the domain configuration called a Barkhausen jump. Such jumps are manifested in the measurement of magnetization processes as high frequency noise on the otherwise continuous waveforms. Since pickup coils measure the derivative of the flux through their field of view according to equation 5, BN measurements are twice as sensitive to 180° domain activity as they are to 90° domain activity and domain rotation processes.

EXPERIMENTAL SETUP

In order to control $\Phi$, the magnetic circuit shown in Figure 1 is used. A NI PCI-6229 DAQ in conjunction with LabVIEW software provides an arbitrary periodic waveform, $V_{REF}$, to the positive terminal of the audio amplifier. The negative terminal is connected to either the shunt voltage ($V_s$) or the feedback coil voltage ($V_f$) via a digital switch consisting of two H11F3 FETs, allowing $I$ control or $d\Phi/dt$ control respectively.

To ensure $\Phi_{REM} = 0$, the circuit is put through a degauss cycle before each measurement. The $d\Phi/dt$ control circuit is limited by DC stability and noise in the feedback coil to a minimum flux rate of 5 T/s in the ferrite U-core. The amplifier is voltage-limited at rates above 30 T/s. The pickup coil is band-pass filtered from 3-200 kHz, and amplified with a gain of 1000, producing $V_{SBN}$.

To produce the raw data shown in Figure 2, $V_{SBN}$ and $V_f$ are simultaneously sampled at 2.5 MHz by a NI PCI-6133 DAQ, providing a measure of $d\Phi/dt$ and $\Phi$ for every $V_{SBN}$ sample. $V_f$ and $V_s$ are also sampled at 30 kHz by the PCI-6229, providing a measure of the hysteresis loop of the circuit. Measurements were acquired with square $d\Phi/dt$ waveforms to demonstrate the rate dependence of BN, and are specified by the flux density rate in the ferrite U-core,

$$\frac{dB_{CORE}}{dt} = \frac{-V_f}{N_f A_{CORE}},$$ \(7\)

![FIGURE 1](image_url). The experimental circuit schematic for surface Barkhausen noise measurements, capable of both current control and flux control via optically isolated digital switching. This apparatus uses a surface mounted solenoid pickup coil.
in units of T/s. Note that since the flux is measured in the core, there is distortion of the flux waveform in the sample as it saturates. Skin depth effects were minimized by choosing a 0.45 mm sample thickness. The sample is a lamination of SiFe steel from a transformer core.

**FULL ANALYSIS**

Barkhausen events are transient \(\frac{dM}{dt}\) impulses in the volume of the sample. It is possible to detect elemental BN events of a single domain overcoming a single pinning barrier, but for industrial steels \(\frac{dB_{CORE}}{dt}\) will be on the order of 1 mT/s [1,5]. Even when \(\frac{dB_{CORE}}{dt}\) is greater than 1 T/s BN is still evident, as elemental events combine to produce larger events that can also be individually detected.

In this system individual BN events are indexed using peak detection algorithms built in to LabVIEW. The algorithm fits a 2nd order polynomial to each set of 3 sequential samples or more whose values are more than 5\(\sigma\) above the background noise in the pickup coil. The index of each peak in the \(V_{BN}\) waveform along with its amplitude is recorded.

To ensure that filtering and amplification of the pickup coil signal is optimal, the mean of all detected peaks is computed and displayed. Filtering is adjusted so that the mean event is represented by a single peak. The dependence of the mean event amplitude on \(\frac{dB_{CORE}}{dt}\) from 10 to 30 T/s is shown in Figure 3.

The pulse height distribution (PHD) of BN events is often shown as a plot of event probability vs. amplitude. With the present system, the PHD can be calculated for any \(\Phi\) along the hysteresis cycle by binning events according to the specific point in the hysteresis cycle \(\text{sgn}(\frac{d\Phi}{dt})B_{CORE}\), where \(\text{sgn}(x) = x\cdot|x|^{-1}\) at which they occurred, as in Figure 4a. To simplify presentation, the mean event amplitude and the probability of an event occurrence can be extracted for each bin as shown in Figure 4b and Figure 4c respectively.
FIGURE 3. The mean event from the SiFe sample at flux rates of 10, 20 and 30 T/s.

FIGURE 4. a) The pulse height distribution of BN events in the SiFe sample at a flux rate of 20 T/s, b) the mean event amplitude at 10, 20 and 30 T/s, and c) the mean event probability at 10, 20 and 30 T/s, shown as a function of $\text{sgn}(d\Phi/dt)B_{\text{CORE}}$. 

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FIGURE 5. a) The hysteresis loop of the magnetic circuit for three different air gaps between the excitation magnet and the sample. b) The mean event amplitude of BN signal for the same three air gaps, shown to be consistent under flux control, when plotted against the $\text{sgn}(d\Phi/dt)B_{\text{CORE}}$ parameter.

This binning demonstrates that the BN statistics change significantly around the hysteresis cycle, with larger events favored at specific $\text{sgn}(d\Phi/dt)B_{\text{CORE}}$ values. To understand this full PHD, modeling of domain processes in the material is required, including the pinning site potential, domain formation processes, domain wall motion, domain population refinement, and domain vector rotation.

A plot of $B_{\text{CORE}}$ vs. $\langle H \rangle$ yields the hysteresis loop of the magnetic circuit. The relationship between $B_{\text{CORE}}$ and $\langle H \rangle$ is sensitive to the introduction of air gaps into the magnetic circuit, as is shown in Figure 5a by increasing the lift-off from 0 to 600 $\mu$m.

The use of the PHD is demonstrated in Figure 5b to show that with flux control there is no significant change in the mean event amplitude with respect to $\text{sgn}(d\Phi/dt)B_{\text{CORE}}$ under lift-off conditions. The mean event probability is similarly consistent under lift-off, though not shown. Therefore, with flux control, measurement of $\langle H \rangle$ is unnecessary if sample BN is of primary interest.

SINGLE PARAMETER ANALYSIS

The following is a set of independent parameters useful for simplifying analysis and clarifying trends in BN data. The parameters are computed from the raw $V_{\text{SBN}}$ waveform, and are related to the more complete BN description presented in the full analysis section.

The number of events is the sum of all detected events from the LabVIEW peak detection algorithm, and is equivalent to integrating the probability of an event occurrence over the range of flux in the BN cycle. The number of events is shown as a function of $B_{\text{CORE}}$ peak-to-peak and $dB_{\text{CORE}}/dt$ in Figure 6a and 6b respectively. If the probability of event occurrence is uniform, then the number of events is simply a linear function of the peak applied flux. The higher the flux rate, the fewer events are detected, as the signals from elemental events combine.

The root-mean-square (rms) Barkhausen voltage ($B_{\text{rms}}$) is the rms $V_{\text{SBN}}$ amplitude for values greater than the specified background threshold. $B_{\text{rms}}$ is equivalent to the mean event amplitude over the range of flux in the BN cycle. Figure 6c shows the effect of averaging over the envelope shown in Figure 4b. Figure 6d shows that the $B_{\text{rms}}$ has an approximately linear relationship with $dB_{\text{CORE}}/dt$.

The Barkhausen noise energy ($B_{\text{energy}}$), sometimes called the BN “intensity,” is the time integral of the squared $V_{\text{SBN}}$ waveform for values greater than the specified background threshold, and relates to the total energy emitted by Barkhausen noise. It is equivalent to integrating the PHD over the range of flux encompassed by the BN cycle.
Since both positive and negative BN events are detected, as $dB_{\text{CORE}}/dt$ increases some number of events adds destructively, decreasing the $BN_{\text{energy}}$, as shown in Figures 6e and 6f.

**SUMMARY**

A system for measurement of BN that utilizes flux control for BN excitation, rather than conventional excitation current control, is described. BN measurement parameters that can be extracted under flux control conditions are presented. This is a significant improvement to the conventional excitation current control BN technique, as flux control accommodates not only lift-off but all circuit permeability changes by ensuring sample.
magnetization conditions are reproduced. Flux control will facilitate implementation of test magnets with flexible geometry to accommodate a variety of non-planar surface geometries, in addition to allowing BN measurements through non-magnetic coatings.

As demonstrated by the full PHD, the statistical properties of BN are not uniform around the hysteresis loop, and these differences can be quantitatively resolved in terms of $\Phi$ and $d\Phi/dt$. A variety of analysis techniques have been demonstrated that allow for both a full statistical description of BN as well as a set of single-parameter values that indicate key BN parameters for a given cycle. These parameters will be used to resolve the strain and texture dependence of the BN technique, for the purpose of NDE.

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REFERENCES