AC BARKHAUSEN NOISE IN ELECTRICAL STEELS: INFLUENCE OF SENSING TECHNIQUE ON INTERPRETATION OF MEASUREMENTS

Anthony J. Moses — Harshad V. Patel — Paul I. Williams

Barkhausen noise is an important magnetic phenomenon in applications as diverse as magnetic recording and non-destructive testing. Although discovered almost 90 years ago, the origin and characteristics of Barkhausen noise is still not fully understood. Its sensitivity to changes in the microstructure and stress state of a material can be difficult to measure and interpret. This paper briefly reviews the development of Barkhausen noise measurement techniques up to the present time. Two measurement techniques are presented as examples of measuring Barkhausen noise in electrical steel at typical power frequencies. The first method uses an enwrapping flux sensing double-coil to detect Barkhausen jumps and the second technique uses an inductive ferrite core surface probe. Statistical methods have been applied in analysing the Barkhausen noise signal under various experimental conditions. The effect of changing the separation distance between detection coils on the measurement of Barkhausen noise is used as an example to highlight how the detection method can influence the interpretation of the Barkhausen signal.

Keywords: Barkhausen Noise, Electrical Steel, Pick-up coil, Surface Probe, RMS Analysis

1 INTRODUCTION

The magnetic Barkhausen effect that appears as abrupt changes in magnetisation occurs when a ferromagnetic material is subjected to an external varying magnetic field [1]. The origin of the effect is primarily due to the discontinuous domain wall motion caused by imperfections in the material. The imperfections such as inclusions [2], dislocations [3], grain boundaries [4], and voids form pinning sites, which impede domain wall motion until the external field energy is sufficient to overcome the local energy barriers created by the pinning sites. The domain walls are then able to 'jump' to the next available metastable states. These abrupt changes in magnetisation will induce voltages in flux sensing coils encircling the sample or in inductive pick-up probes at the surface.

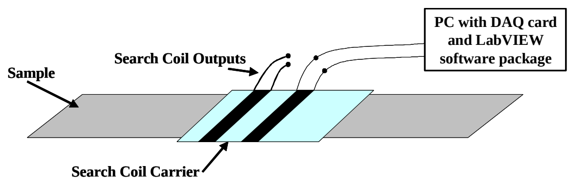
The Barkhausen effect is very sensitive to the changes in the microstructure and stress state of a material and therefore has the potential for exploitation in non-destructive evaluation of ferromagnetic components. This has already been demonstrated in a number of examples including the assessment of the quality of heat treatment in Fe-Cr-B amorphous alloys [5], sub-surface stress analysis in case carburised steel [6], and determination of grinding effects in steel [7].

Barkhausen noise can be measured using a single flux-sensing coil [8], however for a.c. magnetisation the frequency component (i.e. flux density) usually swamps most of the Barkhausen noise information. A better approach is to use two detection coils connected in series opposition [9]. Such an arrangement cancels out the magnetising frequency component and the remaining Barkhausen noise component is then detected using the higher resolution range of the DAQ card. Fig. 1 (a, b) illustrates the two flux sensing methods. Apart from improved voltage resolution, the double flux-sensing coil also effectively senses a greater volume of material, which may lead to differences in Barkhausen noise compared to the single coil method.

Puppin et al. used the two independent coils approach shown in Fig. 1 to detect Barkhausen noise and found that the signals induced in the coils were very similar when the coils are placed nearby whereas a progressive decrease of their correlation was observed by moving the coils apart as shown in Fig. 2 [10].

An alternative method for Barkhausen measurement is to use a ferrite core detection coil with the coil axis placed perpendicular to the surface of the sample as reported by Stewart et al [11] and illustrated in Fig. 3. The ferrite core essentially acts as a magnetic amplifier of the Barkhausen signal induced in the coil. Other materials with high initial permeability such as amorphous alloys can be used as the core as demonstrated successfully in other Barkhausen sensors [12].

Other methods reported for measuring Barkhausen noise include the use of a commercial magnetic head sensor [13] and a commercial system supplied by Stresstech Inc, the Rollscan 200-1 [14].



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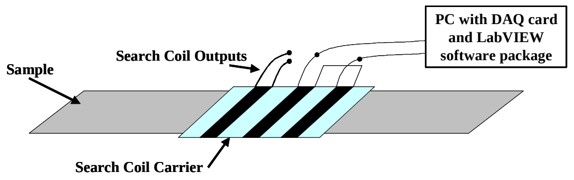
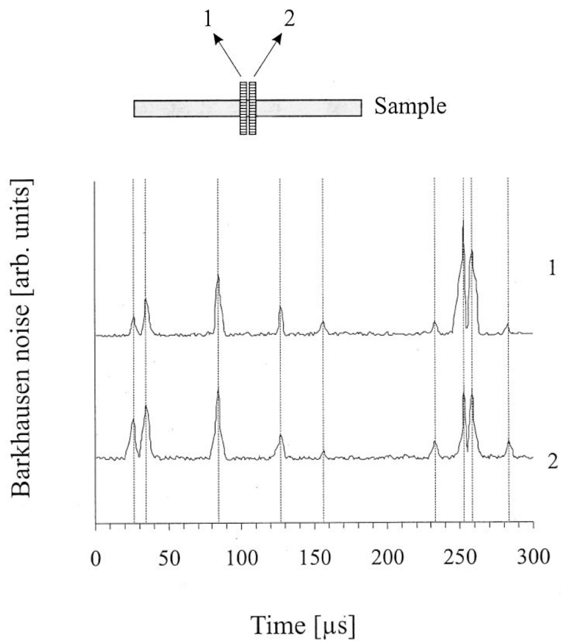


(b)

Fig. 1. Schematic diagrams of sensors. (a) Single enwrapping search coil (b) Double enwrapping search coil wound in series opposition



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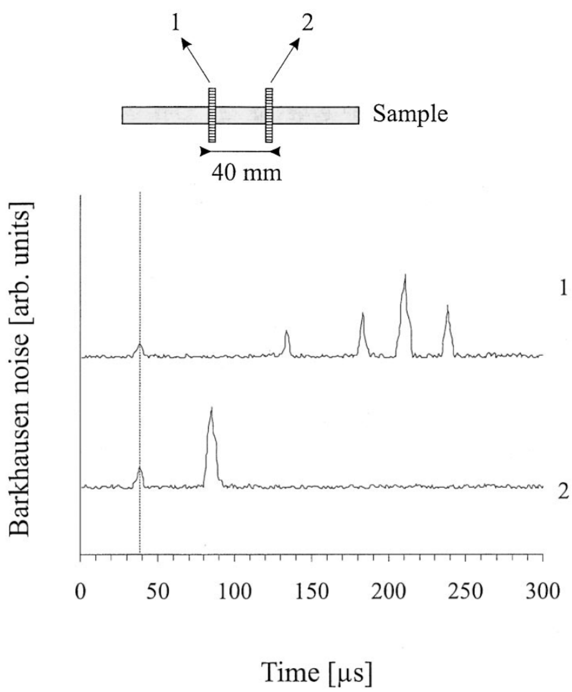


(b)

Fig. 2. (a) Signals when the coils are positioned nearby. (b) Signals when the coils are placed at a distance of 40 mm. [10]

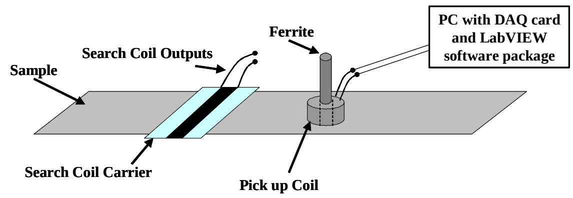


Fig. 3. Schematic diagram of inductive ferrite core surface probe

In this paper we highlight various statistical analysis approaches for Barkhausen noise signal processing. A comparison between the surface probe and enwrapping coil techniques is reported and for the latter the effect of changing the separation distance between pick-up coils on the measurement of Barkhausen noise is also demonstrated.

2 EXPERIMENTAL

A block diagram of a typical Barkhausen noise measurement system incorporating control of the flux density waveform is shown in Fig. 4.

Output waveforms to control the flux density were generated using a National Instruments PCI-6731(E) DAQ card with 16-bit resolution and an update rate of 1 MS/s. The output waveform was fed to the input of the power amplifier. The amplifier's output was connected to the magnetising yoke via an air-core transformer in order to remove undesirable dc components in the magnetising current. The system uses a closed circuit magnetising yoke similar to that specified in the British Standards single sheet tester [15]. The magnetising yoke is 167 mm long with a 32 mm square cross section.

Three pickup coils, each measuring 32 mm in length, 4.8 mm in width and constructed with 80 turns of 0.06 mm diameter enamelled copper wire, were wound around a plastic carrier (Fig. 1(b)) positioned around the sample. Two were wound in series opposition to obtain the Barkhausen noise signal and the third was used to detect the flux density. The signal from the search coils was acquired using a National Instruments PCI-4552AD low noise card with 16-bit resolution, a sampling rate of 204 kHz and a 95 kHz bandwidth. Signals were analysed using the National Instruments software package "LabVIEW". A digital fourth order Butterworth high pass filter with a 3.5 kHz cut-off frequency was used to remove unwanted low frequency interference and environmental noise. The results were averaged over 10 magnetising cycles.

The same data acquisition hardware and software was used for the surface probe measurements, its output voltage was simply substituted for the double coil output. The surface sensors were supplied by *Stresstech Oy* and consisted of a 13 mm length core inside a 1000 turn coil 8 mm in length. The core diameter was 3 mm and the coil position relative to the sample surface remained at a constant height.

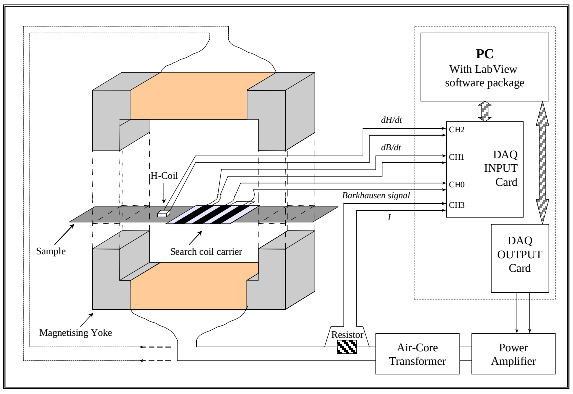


Fig.4. Barkhausen noise measurement system [16].

The British standard for single sheet testing of electrical steel stipulates that the secondary induced voltage shall be maintained as sinusoidal as possible for total power loss measurements. It is preferable to maintain the form factor of the secondary voltage to within ±1 % of 1.11 [15]. However, for Barkhausen noise measurements this is not sufficient, for example in Fig. 5 a distorted dB/dt signal can be seen when the form factor for this signal changes by less than 0.29 % of 1.11, i.e. within the standard. Reducing the deviation from a sinusoidal waveform can be done by calculating the total harmonic distortion (THD) for the signal and then reducing it to an acceptable level, this was done by incorporating digital feedback into the measurement system. For the signal in Fig. 5, the THD is 7.5 % and the corresponding Barkhausen noise signal is shown in Fig. 6.

Fig. 7 is a diagram of the dB/dt signal with a total harmonic distortion reduced to 1.1 % at a flux density of 1.8 T giving a form factor variance of 0.01 % of 1.11. This results in a significant improvement for Barkhausen analysis because the resulting noise signal is measured more precisely with improved repeatability, the uncertainty in repeatability decreased from 9 % to 3 % with a THD of 7.5% and 1.1% respectively. Fig. 8 shows the Barkhausen noise signal measured with reduced distortion of dB/dt. The root mean square (rms) Barkhausen noise was measured at 136 μV and 144 μV for THD's of 7.5 % and 1.1 % respectively. This equates to a 5.9% increase in Barkhausen noise due to the reduction in THD. In all measurements, the THD was set to ± 2 %.

Since Barkhausen noise is stochastic in nature, statistical analysis is required for its interpretation. The analysis parameters that are frequently used to interpret Barkhausen noise include the rms value, sum of amplitudes, power spectrum and Kurtosis.

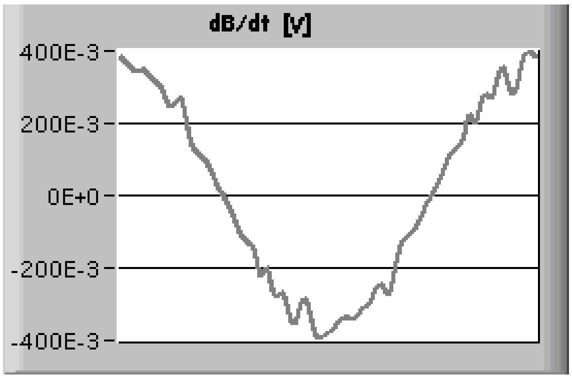


Fig. 5. Distorted dB/dt signal for 50 Hz at 1.8 T

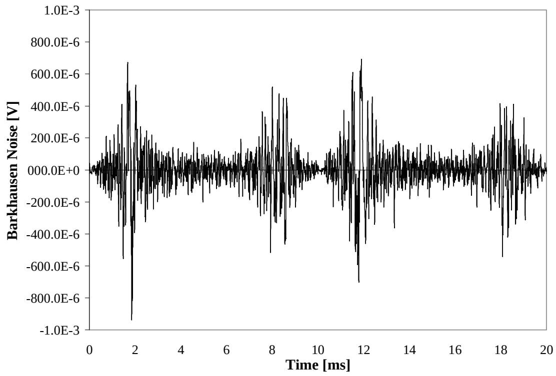


Fig.6. Barkhausen noise signal using distorted dB/dt waveform for 50 Hz at 1.8 T.

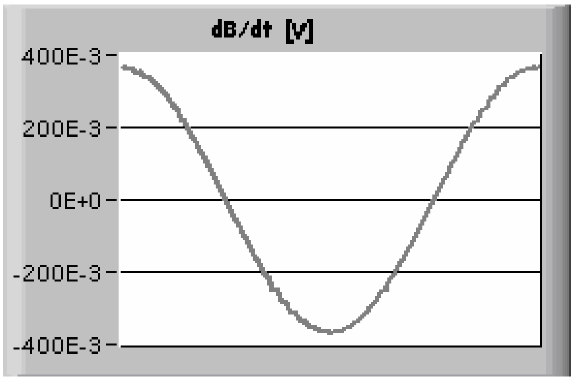


Fig 7. dB/dt signal with improved measurement system for 50 Hz at 1.8 T

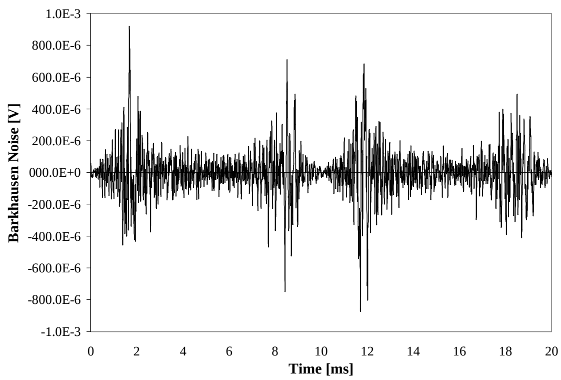


Fig.8. Barkhausen noise signal using improved measurement system for 50 Hz at 1.8 T

The RMS value is easy to measure and is the most commonly measured parameter of Barkhausen noise [16, 17]. This is calculated from:

$$rms \quad \Psi = \sqrt{\frac{1}{N}\sum_{i=0}^{N-1} x_i^2} \tag{1}$$

where N = number of elements in the input sequence and X_i is the Barkhausen noise amplitudes.

The sum of the amplitudes [18] of Barkhausen noise peaks is also convenient but does not count simultaneously occurring peaks or take account of the contribution of peaks of different magnitudes whereas measurement of the power spectrum does contain such information [11]. The power spectrum is calculated as follows:

$$S_k(f) = X_k \cdot X_k^{compl.\,conj.} = |X_k(f)|^2 \tag{2}$$

where $X_k(f)$ = FFT (X_k) and k is the index of the frequency component (harmonic) for which the power has been calculated.

Kurtosis is a parameter that describes the peakedness of a Barkhausen noise distribution relative to a normal distribution. The Kurtosis is calculated from:

$$Kurtosis \quad \sigma^4 = \frac{1}{N}\sum_{i=0}^{N-1}(X_i - \mu)^4 \tag{3}$$

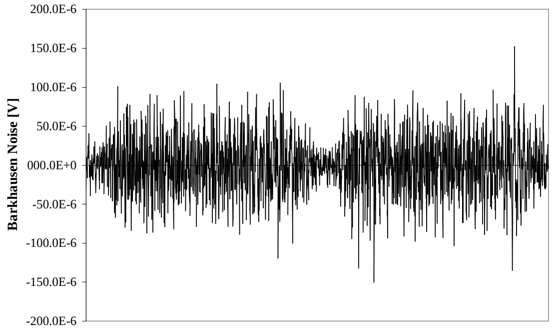
where N is the number of elements in X_i and μ represents the mean value of the sequence [19].

Other methods in use but not investigated here are the mean, standard deviation, pulse height distribution, and FFT. All these methods have been found to be useful in interpreting Barkhausen noise data [17].

3 RESULTS & DISCUSSION

A strip of electrical steel was magnetised sinusoidally at 50 Hz and at peak flux densities in the range 0.3 - 1.8 T. The sample was grain oriented 3% Si-Fe steel (303 mm x 30 mm x 0.27 mm) cut parallel to the rolling direction. The separation distance between the adjacent ends of the two pick-up coils was varied from 5 mm to 40 mm.

Fig. 9 shows Barkhausen noise distributions for two different coil separations. Larger Barkhausen noise amplitudes are seen for a 40 mm coil separation. The difference is even clearer when rms values are calculated. For a 5 mm separation distance the rms Barkhausen noise is 36.1 μV compared to 91.0 μV for a 40 mm separation. This is a 152 percent increase in Barkhausen noise.



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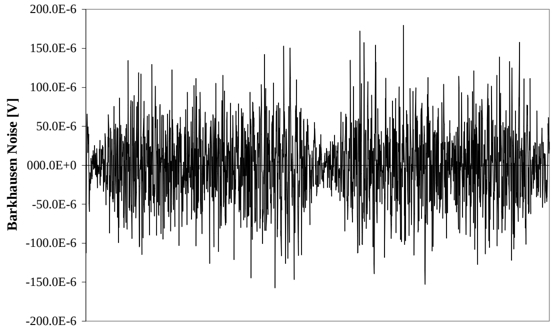

(b)

Fig.9. Barkhausen noise spectrum at 50 Hz magnetising frequency and 1.2 T (a) separation distance of 5 mm (b) 40 mm.

Fig. 10 shows the variation of rms Barkhausen noise with peak flux density. It can be seen that the noise appears to increase significantly as the separation between the two pick-up coils increases.

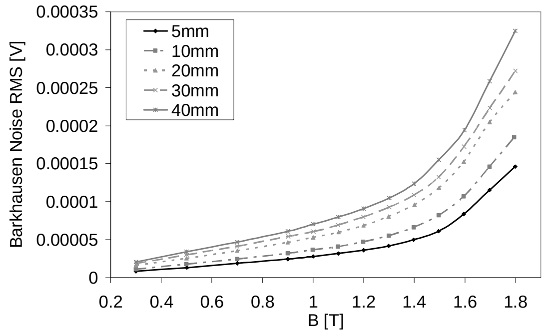

Fig. 10. RMS analysis of Barkhausen noise signal at 50 Hz magnetising frequency vs. magnetic flux density for different distances between pick up coils.

Figs.11, 12 and 13 illustrate that other Barkhausen parameters also change with coil separation but their functional dependencies are not identical.

The results in Fig.10 are also indicative of a spatially varying Barkhausen noise spectrum, as previously stated in [10]. In this case, the degree of Barkhausen noise cancellation decreases with coil separation. For example, there is a 122% increase in rms Barkhausen noise as coil separation increases from 5 mm to 40 mm at 1.8T.

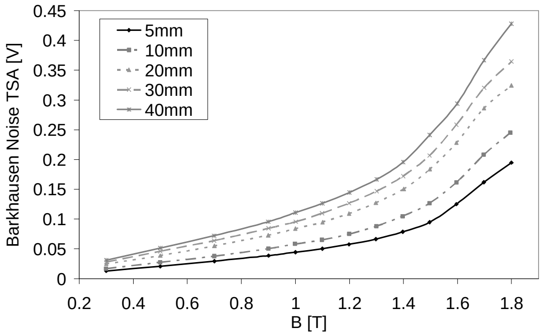

Fig. 11. Total sum of Amplitudes (TSA) analysis of Barkhausen noise signal at 50 Hz magnetising frequency vs. magnetic flux density for different distances between pick up coils

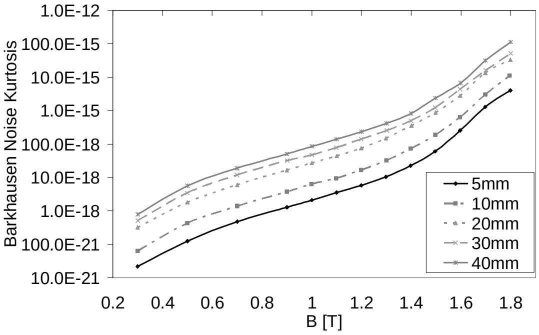

Fig. 12. Kurtosis analysis of Barkhausen noise signal at 50 Hz magnetising frequency vs. magnetic flux density for different distances between pick up coils

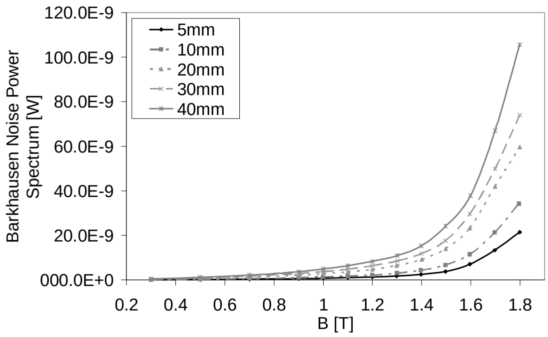

Fig. 13. Power Spectrum analysis of Barkhausen noise signal at 50 Hz magnetising frequency vs. magnetic flux density for different distances between pick up coils

Extrapolating the data in Fig.14 to zero coil separation does not yield zero Barkhausen noise, which is expected if the coils are identical in dimensions and location. The reason for the positive intercept in Fig. 14 may be due to a number of reasons. For instance the pick-up coils may not be identical therefore measured amplitudes will be different. Also by separating the coils this naturally leads to each coil detecting a different Barkhausen spectrum. If the material has significant local variations in Barkhausen activity then a linear dependency with coil separation is unlikely. Only strongly homogeneous materials are expected to produce a linear relationship with coil separation provided each coil picks up an average Barkhausen emission which is representative of the material as a whole.

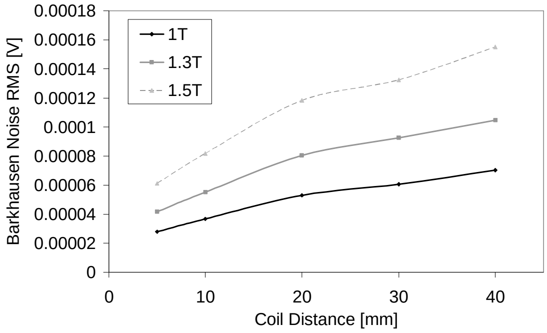

Fig. 14. RMS analysis of Barkhausen noise signal at 50 Hz magnetising frequency vs. distance between pick up coils at 1T, 1.3T and 1.5T.

Fig. 15 compares the outputs of a single search coil, a double search coil wound in series opposition and a ferrite core surface sensor on a sample of commercial 0.27 mm thick grain oriented 3 % silicon steel magnetised from 0.3 T to 1.8 T at 50 Hz. It is interesting that the trends obtained with the ferrite core surface probe are very similar to those of the enwrapping coils although their modes of operation are oriented perpendicular to each other. The relative change of rms Barkhausen noise value with flux density detected by the ferrite core sensor is greater compared to that of the double search coil. The ferrite core sensor output increases more rapidly at high flux density indicating that the different sensors are effectively picking up different Barkhausen noise contributions. The total sum of amplitudes, Kurtosis and power spectrum parameters also show similar trends. This may not be too surprising since the surface probe will detect Barkhausen events in localised regions near to the surface, which may behave quite differently to regions in the sample's interior where detection of events by conventional pick-up methods occurs.

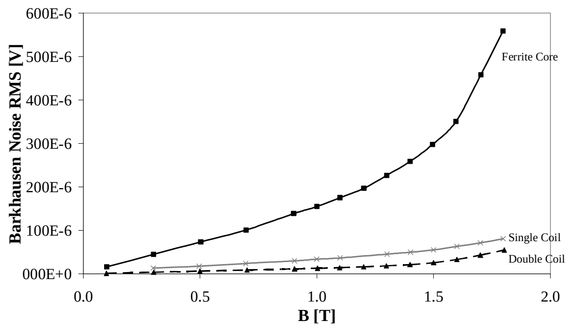

Fig. 15. Variation of normalized Barkhausen Noise RMS outputs of the sensors with flux density at 50 Hz in grain oriented 3 % silicon steel [20].

4 CONCLUSIONS

Barkhausen noise in electrical steel magnetised at 50 Hz has been measured separately using double coil and surface probe techniques. Both methods when analysed using a number of Barkhausen parameters revealed similar trends.

For the double coil method, we have demonstrated that the Barkhausen signal depends on both pick-up coil geometry (separation) and induced flux density.

The surface probe method appears to be an order of magnitude more sensitive to Barkhausen events than the enwrapping coil methods particularly at high flux densities.

Further investigations are required to establish the exact nature of the Barkhausen noise contribution measured by each technique. For example, it is still unclear to what depth in steel the surface probe is capable of detecting Barkhausen events.

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