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1972 J. Phys. D: Appl. Phys. 5 1389

(http://iopscience.iop.org/0022-3727/5/8/305)

J. Phys. D: Appl. Phys., Vol. 5, 1972. Printed in Great Britain. © 1972

The frequency spectrum of Barkhausen noise

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MS received 13 April 1972

Abstract. The spectrum of Barkhausen noise has been measured in iron and analysed using signal analysis techniques. The results suggest that the mean duration of the voltage pulses caused by the domain reversals is less than 5×10^{-5} s and that a domain reversal triggers other domain reversals with a time delay normally of 1 to 2 ms. Delays of up to 10 ms do occur. The results agree with those obtained by Sawada. The technique allows detailed information of the dynamic nature of domain reversals to be obtained quickly and with little sample preparation.

1. Introduction

Barkhausen noise is the signal induced in a search coil, wound round a ferromagnetic material, when the material is slowly magnetized. The noise voltage is induced by discontinuous changes in magnetization or domain jumps which occur in the material (the Barkhausen effect).

The Barkhausen effect (Barkhausen 1919) has been studied extensively since 1919. Tyndall (1924) measured changes in magnetic moment due to single reversals, and most measurements since then have considered isolated reversals, obtained by applying very slowly changing external fields (up to 10 000 s for maximum field to be applied).

Noise induced by externally applied fields modulated at 1 Hz or more can become the limiting factor in the manufacture of low-noise apparatus, so Barkhausen noise is of practical as well as theoretical significance. This noise is not difficult to measure but analysis is not easy: Bunkin (1959) developed an analysis for single-domain jumps which has been extended here to describe the practical case of multiple and non-isolated domain reversals.

1.1. Nature of domain reversals

Williams and Noble (1950) assumed that the temporal dispersion of the reversals causing Barkhausen noise was random, and they used an analysis developed by MacFarlane (1949) which assumed that no eddy currents were present. For random processes Campbell's theorem may be applied. Campbell's theorem was used by Biorci and

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Pescatti (1957) but is probably inappropriate, as domain reversals are not independent, one reversal tending to trigger other reversals in an 'avalanche' effect (Tebble and Newhouse 1953).

2. Experiment

Barkhausen noise was measured in iron using an apparatus similar to that used by Biorci and Pescatti (1957). A drawn iron wire specimen 5·9 cm long and of 0·79 mm diameter was placed in a search coil consisting of two coils each of 4000 turns of 43 SWG enamelled copper wire and length 1·3 cm, separated by a distance of 6 mm. The coils were connected in series but wound in opposite directions to cancel the induced voltage due to the externally applied magnetic field.

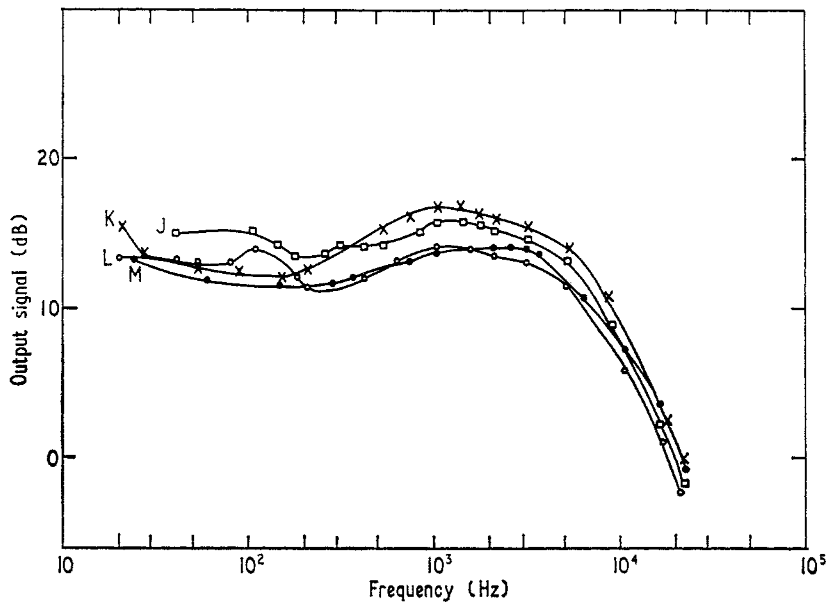

Figure 1. Frequency spectra of Barkhausen noise in iron: curve J, at 19 °C ambient temperature, with a peak external magnetic field of 1335 A m^{-1} modulated at 2 Hz; curve K, as curve J but with a peak field of 1780 A m^{-1}; curve L, as curve J but at 92 °C ambient temperature; curve M, at 134 °C ambient temperature, with peak external field of 1780 A m^{-1} and modulation at 3 Hz. The output signal is 0 dB at 100 μV.

The search coil and specimen were placed in the centre of a solenoid of 2 cm diameter and 12·8 cm long with 455 turns of 35 SWG enamelled copper wire. The solenoid current was supplied from a class AB DC amplifier, and consisted of a triangular wave of frequency varying between 2 and 4 Hz, with maximum currents of up to 1 A peak-to-peak (1780 A m^{-1} peak field).

The noise signal induced in the search coil was amplified and fed to a Muirhead Pametrada spectrum analyser, and the RMS noise voltage was plotted as a function of frequency. The *Q* factor of the analyser was 50. Typical results are shown in figure 1.

3. Theory

The complexity of interaction of the variables precludes a completely analytical approach to magnetic domain behaviour prediction. Statistical methods are required for purposes of mathematical modelling.

The dynamic process of domain reversals as they involve domain reversal interaction is of great practical importance. Theoretical studies of domain reversals have normally assumed independence of domains. Bunkin (1959), considering a single-domain specimen, developed an equation which allowed for domain interaction. His equation is here modified to describe the practical case of the behaviour of non-autonomous domains in a multidomain specimen.

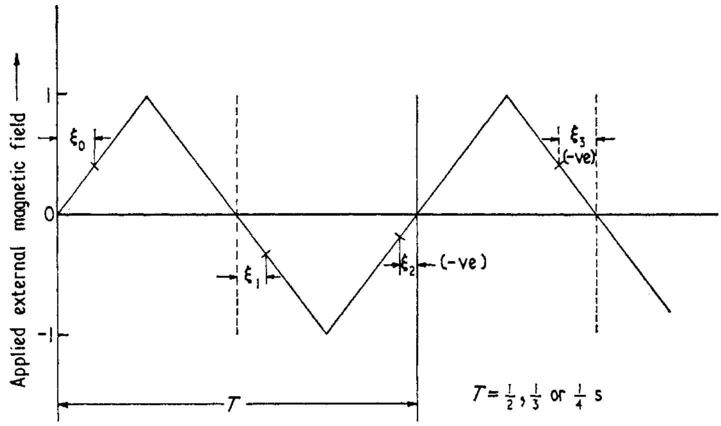

Figure 2. Applied external magnetic field against time showing points of domain reversal.

3.1. Equation development and conditions

Consider a simple model of a single-domain specimen subject to an external magnetic field as shown in figure 2, with zero field at time reference $t=0$; then if the material saturated in each direction, the domain would undergo a magnetic polarity reversal at time

$$t_K = K\frac{T_0}{2} + \xi_K \tag{1}$$

where $K=0, \pm 1, \pm 2, \ldots$. T_0 is the period of the externally applied field and ξ_K is the temporal dispersion of the Kth reversal.

For a single-domain specimen model, with magnetization to saturation and with the form of the induction pulses retained from cycle to cycle but with independent amplitudes,

$$E(t) = \sum_{K=-\infty}^{\infty} (-1)^K a_K v\left(t - \frac{KT_0}{2} - \xi_K\right) \tag{2}$$

where $E(t)$ is the induced voltage and a_K is the amplitude of the pulse due to the Kth domain reversal.

In the presence of cyclical magnetization of a ferromagnetic specimen, the induction EMF and the induction flux $\psi(t)$ must be periodically nonstationary random processes—that is, processes which have statistical properties varying periodically with time. The induction flux and induced EMF $E(t)$ must also obey the induction law,

$$\psi(t)=\text{constant}\times\int_0^t E(t')\,\mathrm{d}t'. \tag{3}$$

Gudzenko (1959) has stated that for the process $E(t)$ to be periodically nonstationary

$$F(0)=0 \tag{4}$$

where $F(\omega)$ is the spectral intensity or the Fourier transform of the time-averaged correlation function of the process $E(t)$. This, by the Weiner–Khintchine theory, equals the power spectral density function of $E(t)$ which was measured in the experiment. The condition of equation (4) is not met by a function described by equation (2). To produce a model which satisfies condition (4), Bunkin developed an analysis assuming that m, the magnetic moment, was constant from cycle to cycle. This is approximately correct. Subsequent EMF pulses must (with respect to area) compensate preceding ones, as there can be no diffusional build-up of the magnetic flux ψ. This is intuitively obvious and also required for Gudzenko's condition to be met. By assuming constant magnetic moment from cycle to cycle this compensation is allowed for.

If m is assumed constant from cycle to cycle, for each domain reversal

$$a_K\,\theta_K=\text{constant}=C \tag{5}$$

where a_K is the amplitude and θ_K the duration of the Kth pulse due to the Kth domain reversal and C is a constant. Both a_K and θ_K are statistically varying quantities. The voltage pulse due to single reversals has been described by Tebble *et al* (1950) but for simplicity may be assumed to be something between a rectangular and an exponential pulse, the spectral output of which is similar for short pulses. The durations of the pulses due to the single-domain reversals are assumed to have a normal distribution and the variance of this duration is given by

$$\sigma_1{}^2=\overline{(\theta_K-\bar{\theta})^2} \tag{6}$$

where $\bar{\theta}$ is the mean duration.

To allow for the effect of preceding domain reversal durations on present pulse duration, a correlation coefficient is introduced:

$$\rho=\overline{(\theta_K-\bar{\theta})\,(\theta_{K+1}-\bar{\theta})}/\sigma_1{}^2. \tag{7}$$

This correlation is assumed small and equal to zero for domain reversals separated by more than one cycle.

The temporal dispersion ξ_K may be conveniently expressed by its characteristic function defined as

$$\phi(\omega)=E\exp\,(\mathrm{i}\omega\xi_K). \tag{8}$$

This expression allows for the variation of the time of reversal from cycle to cycle. Bunkin finally derived an equation

$$F(\omega)=\frac{\omega_0C^2}{\pi^2}\left[\left(\frac{\sigma_1}{\bar{\theta}}\right)^2\left(\frac{\bar{\theta}\omega}{1+(\bar{\theta}\omega)^2}\right)^2|\phi(\omega)|^2\left\{1-2\rho\cos\left(\frac{\pi\omega}{\omega_0}\right)\right\}+\frac{1-|\phi(\omega)|^2}{1+(\bar{\theta}\omega)^2}\right] \tag{9}$$

where $\omega_0=2\pi/T_0$.

Now this expression describes the power spectral density for a single-domain specimen magnetized to saturation in each direction. For the practical case, allowance has to be made for the multidomain specimen, and cases where magnetization is not to saturation and reversals of every domain each cycle ensured. By studying the characteristic function, equation (9) may be used to describe the practical case, and when so studied, the equation gives a rigorous description of the signals measured in the experiment.

Consider equation (9). For each domain of similar size (where C has the same value) the terms in the square bracket may be taken in two parts. For the practical case of multidomain specimens, the autocorrelation of pulse durations, ρ, which is very small even for single-domain specimens, may be assumed to be zero. Thus equation (9) may be rewritten:

$$F(\omega)=A\{BD|\phi(\omega)|^2+(1-|\phi(\omega)|^2)\,E\} \tag{10}$$

where $A=\omega_0 C^2/\pi^2$, $B=(\sigma_1/\bar{\theta})^2$, $D=[\bar{\theta}\omega/\{1+(\bar{\theta}\omega)^2\}]^2$, and $E=1/\{1+(\bar{\theta}\omega)^2\}$. When all domains are considered the constant C in the expression for A is the mean square value of C for all the domains.

Expressions D and E are plotted against frequency in figure 3 for $\bar{\theta}=5\times10^{-5}$ s.

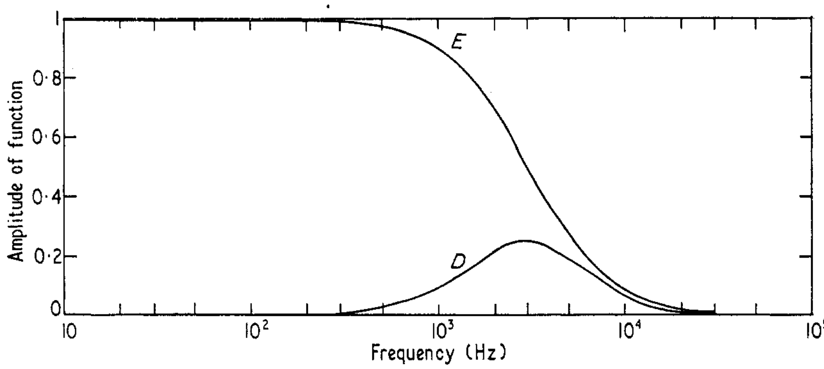

Figure 3. Functions D and E plotted against frequency ($\bar{\theta}=5\times10^{-5}$ s).

4. Results

There are two cases where the signal would be described by only one of these curves:

(i) If the impulse durations were constant, all pulse durations equalling $\bar{\theta}$, the variance $\sigma_1{}^2$ would be zero and the response would follow curve E, modified by the characteristic function $\phi(\omega)$.

(ii) If the temporal dispersion of reversals, ξ, were small in comparison with $\bar{\theta}$, $\phi(\omega)$ would be unity up to high frequencies and the response would be described by expression D.

The practical case is between these two extremes. The results suggest that the temporal dispersion is longer than the average pulse duration, and there is no reason to suppose that the pulse duration remains constant (especially in the multidomain case).

At low frequencies, when $|\phi(\omega)|^2\to1$, it is not possible to determine which of the expressions $BD|\phi(\omega)|^2$ or $(1-|\phi(\omega)|^2)\,E$ predominates, because B and D both have low values. Modulation evident on the plotted results (figure 1) can, however, only be explained as modulation of the characteristic function.

The curves of figure 1 are similar to those obtained by Biorci and Pescatti, which also exhibited modulation.

At high frequencies, when the characteristic function $\phi(\omega)$ approaches zero, the response will follow curve E and by comparison of figures 1 and 3, the response curves (on a logarithmic scale) seem to follow curve E suggesting that a value of 5×10^{-5} s for the mean pulse duration $\bar{\theta}$ is correct.

The curves tend to maximum values at about 1 kHz and this is probably because of the increase of D which is greater than the decrease of E before D approaches its maximum value. Figure 3 shows that, between 1 and 2 kHz, D increases by a factor of 2 while E decreases by about 20%. For curves J and K (at 19 °C) the amplitude change is not as great as that of D and this indicates that the characteristic function decreases from about 500 Hz to 1 kHz, suggesting a temporal dispersion of about 1·5 ms.

At higher temperatures (curves L and M) the response is smoother and decreases little between 1 kHz and 3 kHz which may be caused by an extended decrease of the characteristic function, indicating temporal dispersions of about 1 ms.

Minima and maxima are evident at 200 Hz and 300 Hz on curve J (1335 A m^{-1}, 2 Hz, 19 °C) and curve K (1335 A m^{-1}, 2 Hz, 92 °C) has a peak at 100 Hz. This suggests temporal dispersions of 3 ms, 5 ms, and 10 ms. These results agree with those of Sawada (1948), who found that most domain reversals occurred after a delay of 1 ms with some delayed by up to 15 ms. Sawada also found the mean pulse duration to be less than 10^{-4} s.

At high temperatures, the increase in resistivity of the iron probably reduces eddy currents to give faster triggering.

5. Conclusions

The results confirmed the findings of previous workers. Spectral analysis, by averaging signals and so losing phase information, cannot theoretically extract as much data as auto- and cross-correlation computation, but this method quickly produced useful information of the dynamic processes of magnetization, with no sample preparation (as is required for the static Bitter pattern, Kerr or Faraday tests). The results are for iron only and ferrites could not be studied because of limitations of sensitivity, noise, etc of the apparatus used (Manson 1970), but the method could be applied to ferrites or other materials with improved equipment, and thus provide a useful dynamic testing procedure.

Acknowledgment

The authors are grateful to Professor R S Tebble for advice given and interest shown in this work.

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