THE NOISE GENERATED IN A COIL WITH A FERROMAGNETIC CORE*

By G. Builder† and D. Haneman‡

It is well known that Barkhausen noise will be induced in a coil which has a ferromagnetic core, if the core is subjected to any considerable degree of varying or alternating magnetization due to current flowing in the coil or due to a magnetizing field from some external source. This effect is ascribed to irreversible magnetization processes, such as irreversible domain wall movements, and has been investigated in considerable detail. It has recently been utilized to estimate the amount of the contribution of such irreversible processes to the total magnetization (Tebble, Skidmore, and Corner 1950).

* Manuscript received September 1, 1954.

† School of Physics, University of Sydney.

‡ School of Physics, University of Sydney; present address, Division of Radiophysics, C.S.I.R.O., University Grounds, Sydney.

It is also well known that the insertion of a non-magnetic conducting core into a coil will increase the thermal noise generated in the coil, and that the total noise depends on the effective coil resistance, with the core present, in accordance with Nyquist's formula. This increase in noise can be interpreted on the one hand as due to thermal fluctuations in the core and, on the other hand, as corresponding to the losses caused by eddy currents in the core when an alternating test voltage is applied to the coil terminals to measure its resistance.

Furthermore, if such a conducting core were also endowed with ideal magnetic susceptibility (i.e. if it were a homogeneous isotropic material displaying a perfectly linear relation between magnetizing field and magnetization) the consequent increase in magnetic flux and eddy currents associated with a current through the coil, or associated with thermal fluctuations, would result in an increase in coil resistance and a corresponding increase in the thermal noise generated in the coil. It is to be emphasized that this effect is due solely to the increase in flux caused by the ideal susceptibility of the core.

Any real ferromagnetic core must also cause such an increase in thermal noise on account of its conductivity and its finite magnetic susceptibility. This must be true even if the core is not subject to any varying or alternating magnetization which would give rise to Barkhausen noise effects. It is not, however, immediately obvious

(*a*) whether the real ferromagnetic core will contribute still further to the noise because of the departure of its actual properties from the ideal, i.e. because of the non-linearity of its characteristics, or because of its domain structure;

(*b*) whether it is permissible, in spite of the actual ferromagnetic properties of the core, to use Nyquist's formula to calculate the total noise from the measured value of the coil resistance.

It is therefore necessary to consider the conditions under which Nyquist's formula is applicable, and the relevant properties of ferromagnetic materials.

Nyquist's formula.—The mean square value $E_f^2 \mathrm{d}f$ of the noise e.m.f. generated in the frequency range $\mathrm{d}f$, in an electrical circuit of which the impedance has a resistive component R_f at frequency f, is given approximately by

$$E_f^2 \mathrm{d}f = 4kTR_f \mathrm{d}f,$$

where k is Boltzmann's constant and T the absolute temperature of the circuit. Nyquist derived this formula for linear electrical circuits by simple thermodynamic considerations.

To review the conditions under which this formula is applicable, reference may well be made to the definitions used by Callen and Welton (1951) in their derivation of a generalization of it. The formula can be regarded as a special case of a general relation between the fluctuations of a "generalized force" (i.e. voltage), in a linear system in equilibrium, and a parameter which characterizes a dissipative process (i.e. electrical resistance) in the system. A system is said to be dissipative if it is capable of absorbing energy when subjected to a time-periodic perturbation (e.g. alternating test voltage); it is said to be linear if the power dissipation is quadratic in the magnitude of the perturbation.

These definitions emphasize that Nyquist's formula can be used whatever the physical nature of the dissipative processes that determine the value of the electrical resistance; it is only necessary that the system be linear in the sense defined, for the range of conditions of interest, and this corresponds to the common use of the term in reference to electrical circuits.

The fact that ferromagnetic materials exhibit marked non-linearity in many of their practical uses is not necessarily relevant; the linearity of the system under consideration must be investigated specifically, in accordance with the above concepts, under the particular conditions of interest. It is to be noticed that even electrical circuits constructed of non-magnetic materials are linear only under restricted conditions (e.g. metallic conductors at constant temperature) and, on the other hand, that the inclusion in an electrical system of an essentially non-linear device such as a thermionic tube does not necessarily cause the system to exhibit non-linearity if the conditions considered are sufficiently restricted.

The relevant characteristics of ferromagnetic materials.—The first significant investigation of the behaviour of ferromagnetic materials for very small changes in magnetization was that made by Lord Rayleigh (1887). He found that the susceptibility was constant for various samples of iron and steel for magnetizing-field changes up to about 2×10^{-2} oersteds and down to the smallest changes, about 2×10^{-5} oersteds, for which measurements could be made. Many subsequent investigations have confirmed this linearity of the relation between magnetizing field and magnetization for small variations of the magnetizing field, whether there is a steady polarizing field present or not, and irrespective of the magnetic history of the specimen. For our present purposes, a sufficient summary of this work, and of the present views on the magnetization processes involved, is given in a recent paper by Tebble and Corner (1950).

The greater part of the magnetization process is ascribed to irreversible changes commonly associated with the Barkhausen effect; but a substantial part of the process is due to reversible changes such as continuous movements of domain boundaries through successive equilibrium conditions. These changes are not reversible in the thermodynamic sense only because the conductivity of actual core materials permits more or less localized eddy currents to be set up by the changes, with consequent dissipation.

The reversibility referred to does not in itself imply linearity in each of the individual local changes which contribute to the magnetization; but for a core material consisting of a complex polycrystalline aggregate it is to be expected, and it is found, that the total of the individual reversible contributions is linearly related to the magnetizing field.

The term reversible susceptibility is used for the susceptibility of the material to changes in the applied magnetizing field which are so small that Barkhausen effects are not observed. Figure 1, taken from the paper by Tebble and Corner, shows the relation of the measured values of reversible susceptibility $\varkappa_r$ to the magnitude ΔH of the applied alternating magnetizing field, for a specimen of hard-drawn iron. This curve is typical of conditions at the foot of the initial magnetization curve or at values of the steady magnetizing field of the order of the coercive force, where the reversible susceptibility is greatest and the extent of the reversible regions is least. It is seen that, in this case, the measured values of the reversibility are almost constant for values of ΔH up to 10^{-2} oersteds. It is clear from this and similar evidence that there is a linear relation between magnetizing field and magnetization for small variations or alternations in the field.

There does not appear to be any direct experimental evidence relating the eddy current losses associated with this reversible magnetization to the amplitude

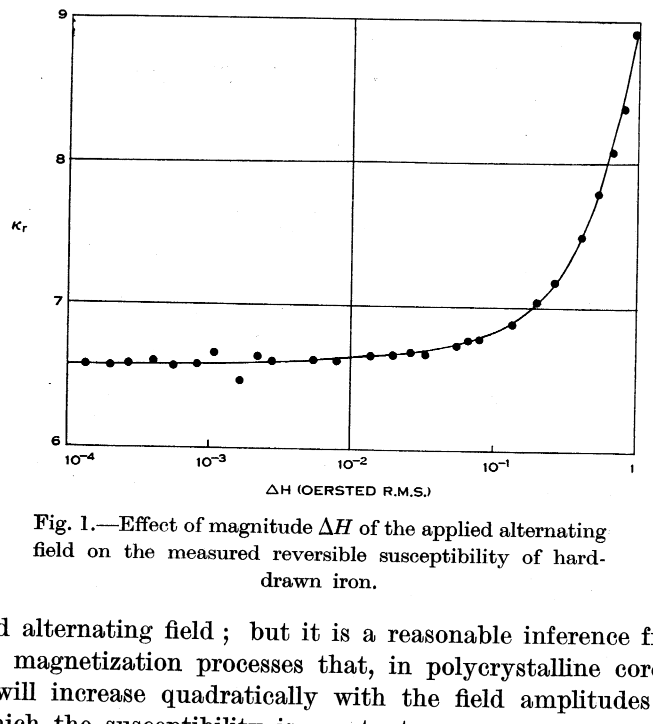

Fig. 1.—Effect of magnitude ΔH of the applied alternating field on the measured reversible susceptibility of hard-drawn iron.

of the applied alternating field ; but it is a reasonable inference from present knowledge of magnetization processes that, in polycrystalline core materials, these losses will increase quadratically with the field amplitudes within the regions in which the susceptibility is constant.

The noise generated in a coil with a ferromagnetic core.—When there is no varying or alternating magnetization of the core, the noise can therefore be calculated using the Nyquist formula, provided that any alternating test voltage applied to the coil to measure its resistance R_f is chosen so that any consequent alternating magnetizing field applied to the core is so small that the magnetization process is linear.

The measured value of the coil resistance R_f will include the effects of the resistivity of the coil windings and of the electrical resistivity of the core, as well as the effect of the constant reversible susceptibility of the core. The increase in noise corresponding to the susceptibility of the core may be interpreted as the result of spontaneous fluctuations in the equilibrium magnetization of the core, or it may be interpreted as the result of increased magnetic flux associated with thermal fluctuation currents.

This investigation was carried out in the School of Physics in the course of work supported by the Research Grants Committee of the University of Sydney.

References

Callen, H. B., and Welton, T. A. (1951).—*Phys. Rev.* **83**: 34.

Rayleigh, Lord (1887).—*Phil. Mag.* (5) **23**: 224.

Tebble, R. S., and Corner, W. D. (1950).—*Proc. Phys. Soc. Lond.* B **63**: 1005.

Tebble, R. S., Skidmore, I. C., and Corner, W. D. (1950).—*Proc. Phys. Soc. Lond.* A **63**: 739.