The Duality that Relates Magnetic Noise to Electric Shot Noise

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***Abstract* — Statistical treatment of the succession in time of the Barkhausen-noise pulses shows that magnetic noise possesses characteristics that are similar to those of electric shot noise. On the other hand, the electric shot-noise intensity in a noisy component is known to be related directly to the square root of the dc current through the component. Hence, it is intriguing to relate in the same manner the magnetic-noise flux-fluctuations to a magnetic entity similar to the dc current in the electric case. The present work is a successful attempt to demonstrate that such relationship exists. This is attained by employing the duality that relates the time-derivative of the magnetic flux to the electric current. The magnetic noise measurements of commercially available thin-film magnetoresistors confirm the applicability of the proposed approach. The noise was generated by exciting the magnetoresistors by an ac magnetic field along their easy axes. The level of the resulted flux time-derivative was changed by varying the excitation frequency.**

I. Introduction

The scientific literature [1] – [4] suggests that magnetic noise possesses characteristics that are similar to those of electric shot noise. This suggestion is due to a statistical treatment of the succession in time of the Barkhausen-noise pulses. On the other hand, the electric shot-noise intensity in a noisy component is known to be related directly to the square root of the dc current through the component. However, there has not been apparently an attempt to relate the magnetic-noise flux-fluctuations directly to a magnetic entity similar to the dc current in the electric case. The present work shows both theoretically and experimentally that this relationship can be attained by employing the duality that connects the time-derivative of the magnetic flux to the electric current.

The scientists who suggested the statistically based theory [1] – [4], performed relatively complicated experiments in order to obtain the spectrum of the Barkhausen magnetic noise. Our point of view, that is based on duality considerations and on comparison of the magnetic noise to electric shot noise, enables us to perform relatively simple experiments. Further advantage is that the interpretation of the experiments also becomes simpler.

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Experimental measurements [1] – [4] result in typical magnetic noise spectrum shown in Fig. 1. Two frequencies, f_1 and f_2, characterize this spectral distribution. The noise spectral-density $S(f_{mn})$ is distributed uniformly between these characteristic frequencies and it falls below f_1 and above f_2. The knee frequency f_1 has a tendency to increase with increasing external excitation field frequency. Frequency f_2 depends on the magnetic and electric properties of the material. Another advantage of the presently suggested approach is in its ability to explain the dependence of the lower knee frequency on the excitation frequency. Further advantage of the present work is in employing thin-film magnetoresistors for the noise measurements. As a result, the fundamental magnetic noise properties are not masked by non-magnetic effects. Namely, there is almost no interference caused by eddy currents and no complications introduced by pickup coils.

II. Theory

The rms value of the electric shot-noise current is given by

$$I_{sn} = \sqrt{2eI_{dc}\Delta f}\ , \tag{1}$$

where e is the electronic charge, I_{dc} is a direct current on which the noise-fluctuations are superimposed, and Δf is the noise bandwidth. It has been shown that the appropriate dual of the electric current is the magnetic-flux time-derivative [5]. Hence, an expression similar to (1) can be obtained in the magnetic case, namely,

$$\frac{d\Phi_{mn}}{dt} = \sqrt{2\,\Phi_m \frac{d\Phi_{ex}}{dt}\Delta f}\ , \tag{2}$$

where $d\Phi_{mn}/dt$ is the rms value of the magnetic shot noise – a dual of the electric shot-noise current, Φ_m is an appropriately chosen elementary magnetic flux, which serves as a dual of the electronic charge, and $d\Phi_{ex}/dt$ is the time-derivative of the magnetic flux through the material – a dual of the electric current.

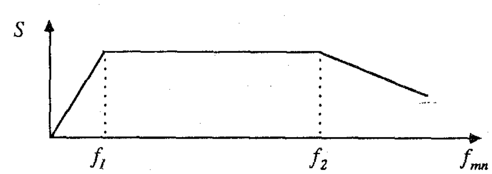

Fig. 1. Spectral distribution of magnetic noise vs magnetic noise frequency.

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Our present objective is to estimate Φ_m which may be regarded as the smallest possible flux change quantity in certain types of magnetic transitions. This evaluation depends on an initial assumption that the magnetization in the material is uniform even at the atomic level. In this case Φ_m can be associated with the average magnetic flux produced by a single atom

$$\Phi_m \cong B_s \cdot A_A \ , \tag{3}$$

where B_s is the saturation inductance of the material, and A_A is the effective average area of the atoms. The following noise-measurements deal with thin-film permalloy magnetoresistive specimens. As a result A_A is estimated here by employing an average distance between atoms (a) in the permalloy lattice (A_A=a^2).

Equation (3) is made more explicable by observing that in the case of a ferromagnet consisting only of one type of atoms Φ_m can be written as follows,

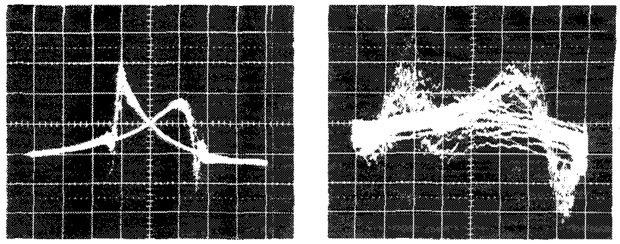
$$\Phi_m \cong \mu_0 \frac{n_0 \mu_B}{a}, \tag{4}$$

where μ_0 is the permeability of free space, n_0 is the number of Bohr magnetons per atom, and μ_B is the Bohr magneton. $n_0 \cdot \mu_B$ is regarded in the present case as an elementary magnetic moment of the atom. Hence, $\mu_0 n_0 \mu_B/(a \cdot A_A)$ is the average magnetic induction in the material.

The statistics governing the flow of elementary charges in the electric case seems to be treated only for a strictly dc current situation. There is probably no need to treat the electric shot noise when the regime of the current through a noisy device differs much from dc. As a result, the rules of duality let us evaluate the magnetic shot noise only when Φ_{ex} is a continuous ramp (since its time derivative is then constant). Flux waveforms which are better suited for experimental work and which do not depart considerably from a ramp are sawtooth or triangular waveforms. However, we found experimentally that the results obtained when Φ_{ex} is sinusoidal are nearly the same as those obtained when Φ_{ex} is triangular, provided that the time integrals of the absolute waveforms values are equal. The magnetic noise in the sinusoidal case (entitled here as sinusoidal excitation) is, therefore, evaluated by employing (2), as follows,

$$B_{mn} = \sqrt{\frac{\Phi_m B_{ex} f_{ex} \Delta f}{\pi A\, k \sqrt{2}\, f_{mn}^{\;2}}}\ , \tag{5}$$

where B_{mn} is the rms value of the magnetic induction fluctuations, B_{ex} is the excitation field amplitude, k is the form factor for a rectified waveform, A is the cross-sectional area of the ferromagnetic specimen, f_{ex} is the excitation frequency, and f_{mn} is the noise frequency. The magnetic shot noise is expected to behave according to (5) only for periods of time, that are shorter than the ac excitation period. Hence, the noise spectrum is expected to be flat only for frequencies above f_{ex}.



(a) (b)

Fig. 2. Output signal of KMZ10 type magnetoresistor vs easy-axis excitation field. The excitation field is sinusoidal of 10 Hz frequency. (a) Amplitude of the excitation field is about 1.0 kA/m. Y=1.5 mV/div. (b) Amplitude of the excitation field is about 250 A/m. Y=0.6 mV/div.

III. Experiments

We used commercially available thin-film magnetoresistors (MR's) to check the theory described above. The magnetization variation in MR's can be arranged to consist mainly of Barkhausen jumps. This is possible as a result of the strong artificially induced anisotropy [3], [4]. MR's are also suitable for the experiments due to their direct (with no need for pickup coil) transformation of magnetic field into electric voltage. Moreover, their operation-frequency range is wide (up to 1 – 10 MHz) and begins at dc. Two types of commercially available MR's were used for the experiments: MR's of KMZ10 type made by Philips, and MR's of HMC1002 type made by Honeywell. Alternating magnetic field, which is applied along the MR's easy axis, may generate strong magnetic noise. The intensity of this noise depends on the amplitude of the excitation field. Fig. 2 (a) shows that the magnetic noise fluctuations occur mainly at instances where the magnetization of the material changes abruptly. The magnetic noise is suppressed when the excitation field amplitude becomes sufficiently large to saturate the MR material (Fig. 2 (a)). This noise behaviour enables us to choose such an excitation amplitude, that causes the magnetization process to be noisy most of the time (Fig. 2 (b)). The resulted noise is, therefore, nearly at its maximum value. The corresponding amplitude of the excitation field was found experimentally to be about 250 A/m for MR's of type KMZ10 and about 500 A/m for MR's of type HMC1002. These amplitudes were maintained constant in our further experiments. The frequency of the excitation field was chosen to be 10 Hz, 100 Hz, 1 kHz, and 10 kHz. The waveform of the field was sinusoidal (k=1.11). Fig. 2 (b) presents the output signal of MR type KMZ10, when the excitation field frequency f_{ex}=10 Hz. Fig. 3 and Fig. 4 present the experimental noise spectra of the MR, when it is excited by magnetic fields of different frequencies. The series of discrete spectral components, that appear in association with the continuous noise spectrum in Fig. 3, represent harmonics of the excitation frequency, that result directly from the nonlinear MR's characteristic.

Spectra of the theoretically expected magnetic-noise voltage are shown in Fig. 4. They have been obtained by converting the B_{mn} in (5) to the corresponding voltage fluctuations (rms) in the following way

$$V_{mn} = s\sqrt{\frac{\Phi_m \mu' H_{ex} f_{ex} \Delta f}{\pi A\, k\sqrt{2}\, f_{mn}^2}}, \qquad (6)$$

where s is the sensitivity of the MR, μ' is the MR apparent permeability [6] in the direction of the easy axis, and H_{ex} is the amplitude of the excitation field. The sensitivity of the KMZ10A MR is about 0.1 μV/nT (for operating voltage of 6 V), μ' is about 2.0, and cross-sectional area of the MR A= 0.033×30 μm2. It has been found that a value of Φ_m of about 1.5×10^{-20} Wb is needed in order to best satisfy the experimental results shown in Fig. 4. Fig. 4 demonstrates close fit of the theoretical and the experimental spectra of the magnetic-noise voltage for the whole range of the noise frequency f_{mn}. Fig. 5 shows that all the spectra of the $(1/\sqrt{\Delta f})\cdot dV_{mn}/dt$ at frequencies larger than the excitation frequency are flat, which resembles the electric shot noise spectrum. The results shown in Fig. 5 are directly related to $d\Phi_{mn}/dt$ in (2).

The theoretical value of Φ_m can be obtained by (3). The saturation induction of the MR material (80 Permalloy) in (3) is about 1 T and the average interatomic distance is about 2×10^{-10} m [6]. Hence, the theoretical value of the elementary magnetic flux is about 4×10^{-20} Wb. This value is of the same order as that of the experimentally obtained value $\Phi_m \cong 1.5\times10^{-20}$ Wb. The present approach is further supported by a series of similar measurements, where MR's of type HMC1002 Honeywell have been used.

IV. Conclusions

The present work demonstrates, that the magnetic noise can be interpreted as being a form of shot noise. This approach is supported here theoretically by employing the rules of duality that relate magnetic phenomena to electric phenomena. The form of the experimentally obtained spectra is also typical for shot noise in possessing a relatively wide plateau. The reason for the fall, however, of the spectra towards low frequencies becomes explicable in the present work due to the observation made in concluding section II on the influence of the excitation frequency. It is also interesting that the relatively coarse approach suggested in the work for evaluating elementary flux jumps predicts a value that is not far from the one obtained through the experimental work.

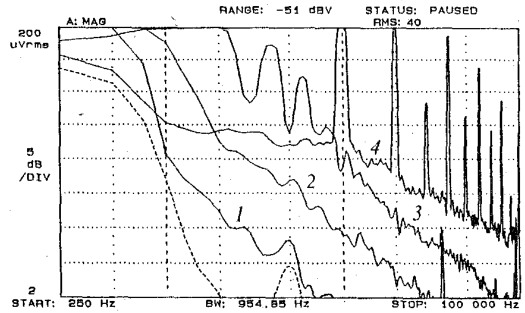


Fig. 3. Experimentally obtained spectra of the magnetic noise produced by KMZ10 type magnetoresistor. *1* $-f_{ex}$ =10 Hz, *2* $-f_{ex}$ =100 Hz, *3* $-f_{ex}$ =1 kHz, *4* $-f_{ex}$ =10 kHz. Dashed line shows spectrum of the total noise induced by the measuring system and the environment.

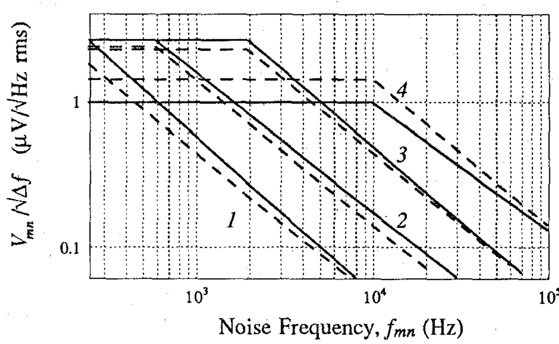


Fig. 4. Simplified representation of the spectra in Fig. 3. Dashed lines show the theoretically obtained spectra of the magnetic-noise voltage.

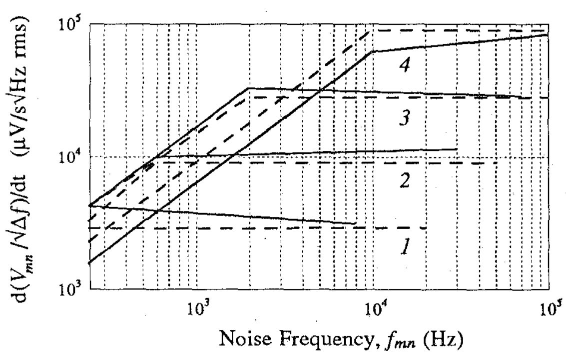


Fig. 5. Spectral density distribution of the time-derivative of the magnetic-noise voltage in Fig. 4.

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