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MEASUREMENTS AT VERY LOW FLUX DENSITY AND POWER FREQUENCIES

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Dithering and averaging allows digital "suppression" of the noise in a detected signal by a factor $\sqrt{n}$, where n is the averaged readings number. If the signal contains sufficient random noise (requirement for dithering) the effective resolution of a data acquisition card can be increased. The measurements described in this paper were performed with a 12-bit data acquisition card and it was found that the voltage resolution could be improved by over 5 bits with averaging (from up to 10 000 cycles). This means voltages lower than the card's resolution can be easily detected with the appropriate digital processing of the measured signals.

Keywords: measurement, low flux, dithering, averaging, noise

1 INTRODUCTION

The flux density, B, in soft magnetic materials (*eg* electrical steels) is usually detected by means of a search coil wrapped locally around a magnetic core, in which the B is to be measured (Fig. 1). The voltage V induced in the coil is proportional to the number of turns N, cross-sectional area A and the rate of change of B, *ie*,

$$V = -N\,A\,\frac{dB}{dt} \tag{1}$$

Consider a periodic, time varying, low magnitude flux density, where the induced voltage is potentially low and noisy. Usually, the physical dimensions of the magnetic core are fixed, so the value of A cannot be changed. Conversely the number of turns can be increased in most cases to produce a higher voltage output. However, N cannot be increased indefinitely – for example, in normal laboratory testing of electrical steel, it is possible to wind a coil with 100, 1000 or even 10000 turns, but eventually a space occupied by the coil becomes a problem, as well as the stray flux around the core. The output voltage can be amplified before measurement, but this might introduce additional magnitude and phase errors, as well as additional noise caused by thermal agitation of the electrons in a conductor – such noise will of course be also be amplified.

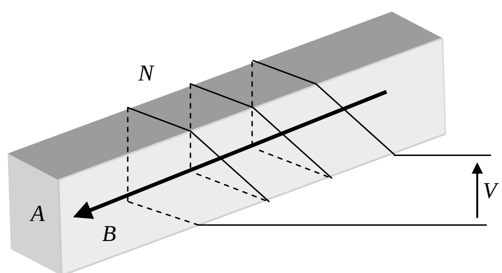

Fig. 1. A coil wrapped around a core

In certain applications, such as magnetic shielding and instrument transformer cores, the magnetic material can be subjected to a very low AC magnetizing field.

Under such conditions the flux density induced in the sample is very low and the resulting voltages induced in coils used for measurement or testing will also be very low [1].

If the voltage is not sufficiently large, a useful technique to improve accuracy of its measurement is dithering and averaging. According to theory [2], averaging can significantly improve the accuracy of signal measurements and other quantities derived from it [3].

The averaging allows digital "suppression" of the noise in the detected signal by a factor $\sqrt{n}$, where n is number of averaged readings. Moreover, if the voltage signal contains sufficient noise (requirement for dithering) the effective resolution of a data acquisition card can be increased.

Fig. 2 shows a simulation of dithering and averaging. An ideal "clean" signal (a) quantised with 3-bit resolution (b) results in visible steps in the processed signal. If the search coil voltage signal is "clean", then the "steps" will occur always at the same locations and no amount of averaging will improve the shape of the processed signal.

For the noisy input signal (c) the quantisation steps are also clearly visible (d). However, if the noise has random character, then the quantisation steps will occur generally at random locations whilst the real signal will remain unchanged.

Therefore, the quantisation steps can be averaged out and the processed waveform will tend to approach the "true" ideal signal. By averaging from 50 readings (the full cycle is averaged from 50 single cycles) the processed signal looks like (e) and two effects are obtained: noise suppression and better accuracy in the ideal signal. In fact, this becomes comparable with a signal with much lower noise (decreased by a factor of $\sqrt{50} \approx 7$ times) and quantised with 6-bit resolution (f). Hence, a resolution enhancement by 3 bits is obtained (g), and with averaging from more cycles it is possible to achieve even better representation of the ideal signal, without any loss in measurement accuracy, provided that the signal triggering is ideal.

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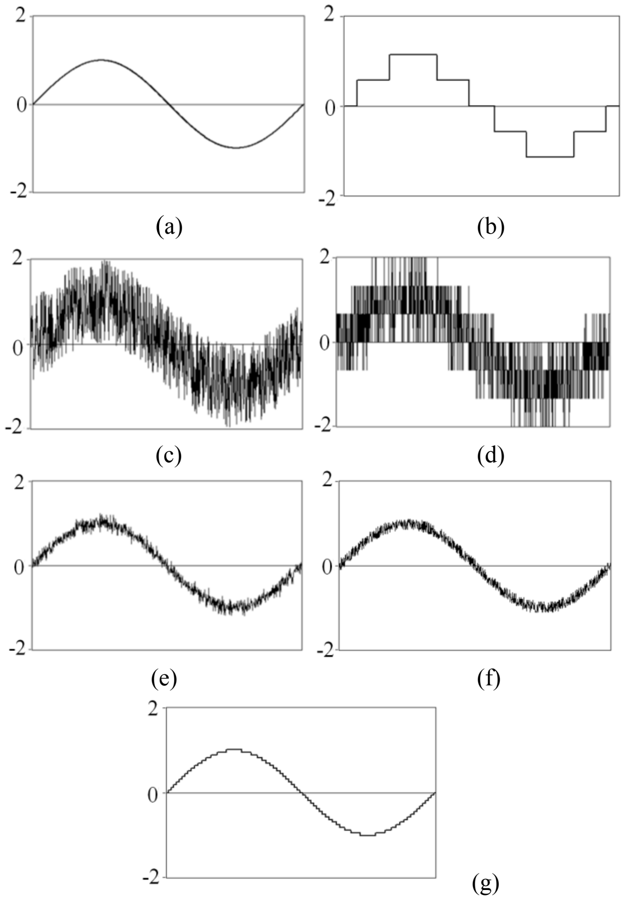

Fig. 2. Resolution improvement simulation by means of dithering and averaging: (a) — ideal signal without noise, (b) — ideal signal quantised with 3-bit resolution, (c) — noisy "real" signal, d) noisy signal quantised with 3-bit resolution, (e) — noisy signal quantised with 3-bit resolution and averaged from 50 random readings, (f) — noisy signal quantised with 6-bit resolution without averaging and with noise suppressed by a factor of 7, (g) — ideal input signal quantised with 6-bit resolution.

2 MEASUREMENT SYSTEM AND RESULTS

Measurements were performed on 30 mm x 305 mm x 0.27 mm single strips of grain-oriented (GO) and non-oriented (NO) electrical steel. The sample was magnetically short-circuited with a two C-type yokes, as shown in Fig. 3. The primary (10 turns) and secondary (2000 and 1090 turns) coils were wound directly around the sample (primary coil was wound over the secondary winding).

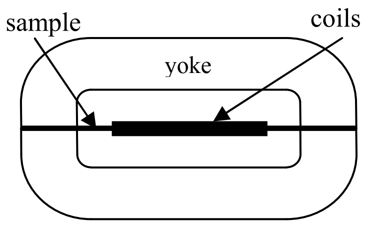

Fig. 3. Arrangement of single strip sample, yokes and coils

The measured primary current and secondary voltage signals were processed by means of a data generation and acquisition card (NI, PCI-6115). The voltage signal generated at the output of the card was passed through a variable signal attenuator (potentiometer), fed to a variable gain power amplifier, and via an isolating transformer to the primary coil. The voltage induced across the secondary winding was fed back to the data acquisition card. All signals were processed numerically in LabVIEW (Fig. 4).

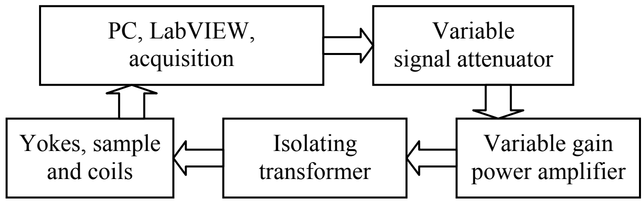

Fig. 4. Block diagram of the magnetising setup

Under sinusoidal flux density it is possible to derive the peak voltage induced in the secondary winding at a given flux density amplitude (Table 1). The equation used to calculate this is:

$$V_{peak} = 2\pi f \ B_{peak} N_2 A \tag{2}$$

where: V_{peak} – is the peak value of induced voltage, f – is magnetizing frequency, B_{peak} – is peak flux density, N_2 – is number of turns of the secondary winding, A – is sample cross-sectional area.

The 12-bit data acquisition card has the lowest voltage range of +/- 200 mV, which translates into around 100 µV resolution of the smallest detectable voltage change. As can be seen from table 1, at 50 µT the amplitude of the sinusoidal voltage is around 250 µV which is not much higher than the card smallest resolution step. Such signals cannot be normally detected with sufficient accuracy.

Table 1. Voltage amplitude at various flux density levels (for 2000 turns and sample 0.27 mm thick)

B_{peak} (mT)	V_{peak} (mV)
10	50.9
0.1	0.509
0.05	0.254

However, because the relatively high resistance of the coil (2 kΩ) the induced secondary voltage contained a large amount of random noise (Fig. 5). After averaging the noise is suppressed by $\sqrt{n}$ (in Fig. 5 by 10 and 100 times, respectively) and at the same time the resolution is improved. The card has resolution of 0.1 mV, whereas the measured signal has amplitude of 0.5 mV so normally the quantisation steps should be visible (as in Fig. 2b and 2d). However, the averaged waveform is "smoothed out" by averaging of the random noise together with the real signal being measured, and no quantisation steps are visible within the noise for the waveform averaged from 10 000 cycles.

The improvement of the resolution is in the first approximation proportional to the $log_2(\sqrt{n})$ as shown in Fig. 6. As can be seen, averaging from 1000 readings improves the resolution by up to 5 bits, which makes a 12-bit card comparable to a 16-bit card and in such a case the overall measuring accuracy of the data acquisition card becomes more important that the voltage resolution [4].

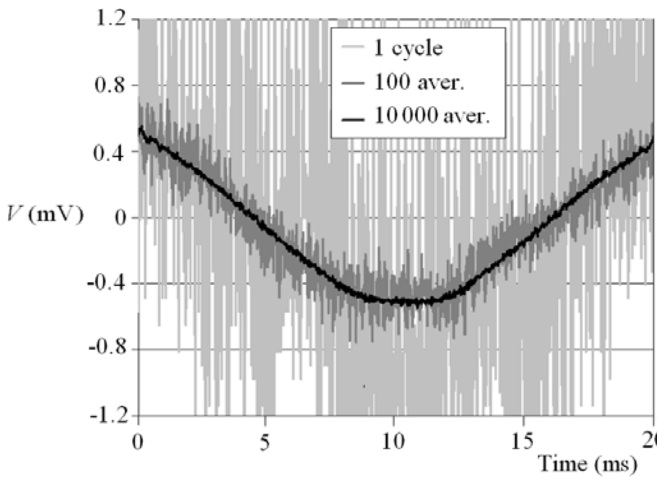

Fig. 5. Voltage waveforms at 0.1 mT (V_{peak} = 0.5 mV) averaged from 1 100 and 10 000 cycles (50 Hz).

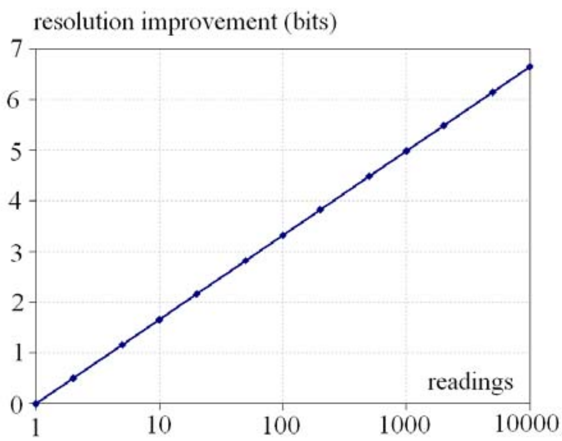

Fig. 6. Improvement of resolution *vs* averaging

3 EXAMPLES OF MEASUREMENTS

The dithering and averaging was used recently [1] and it proved that flux density can be effectively detected down to µT range in a single strip of electrical steel. Fig. 7 shows an example of B-H loops (normalised curves) measured at 50 µT, 5 mT and 500 mT. Noise is visible only in the loop measured at 50 µT (peak voltage 250 µV), but the magnitude and shape of the signals are preserved.

There is relatively little noise in the B-H loops shown in Fig. 7 (as compared to Fig. 5). This is because the voltage induced in the coil must be integrated for the flux density calculation. This provides further smoothing of the noise – compare the voltage waveforms shown in Fig. 5.

However, the instantaneous magnetic field H is calculated from the magnetising current $H=N_1 \cdot I/l$, where N_1 – is number of turns of primary coil, I – is instantaneous magnetising current, l – is magnetic path length), which is measured by means of shunt resistor (in this case 0.48 Ω). The voltage drop across the resistor is therefore also low at low flux density and the measured values can also drop below the resolution of the card.

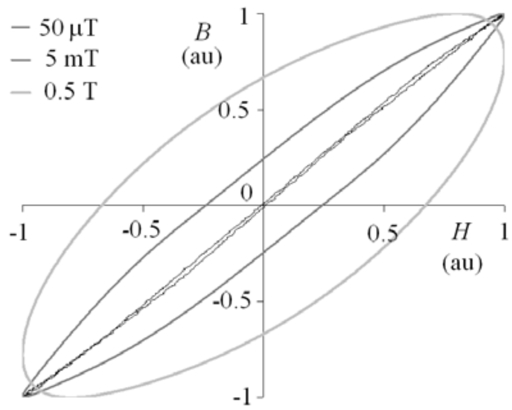

Fig. 7. Normalized B-H loops at 50 µT, 5 mT and 0.5T for GO at 50 Hz

Fig. 8 shows the calculated magnetic field waveform as detected by means of a shunt resistor. As can be seen the waveform measured for one cycle contains large noise, but also the signal level is comparable to the resolution of the card (the arrows indicate visible quantisation steps). After averaging from just 100 cycles the resolution of the card is visibly improved, and further improvement is achieved by averaging from a greater number of cycles, where the quantisation steps are not visible at all.

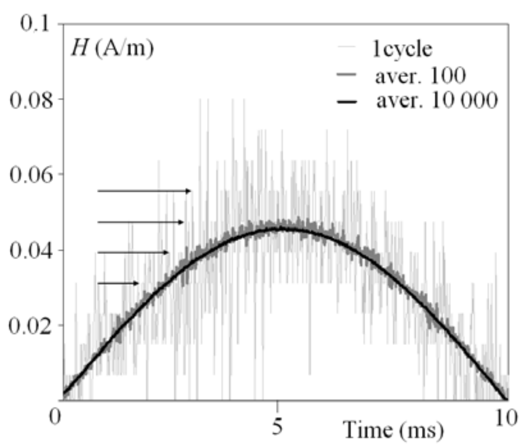

Fig. 8. Calculated magnetic field waveform (half a cycle) for GO at 0.1 mT, 50 Hz (from Fig. 5), the arrows indicate visible quantisation steps.

Because the averaging not only suppresses the noise but also retains the original shape of the waveform this allows measurement of permeability (related to the peak values of *B* and H) and power loss (related to the area of the B-H loop).

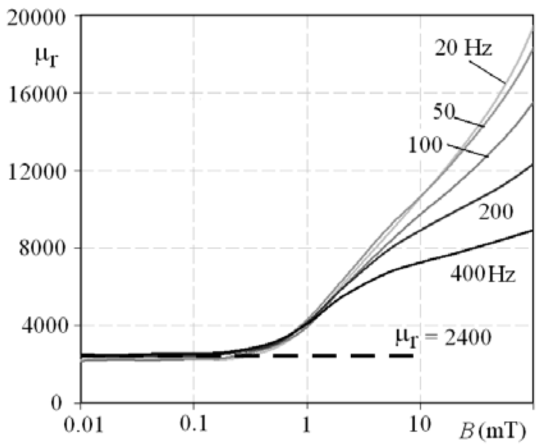

Fig. 9. Permeability curves for GO material at various frequencies from 10 μT to 100 mT

The permeability of GO was measured over a frequency range from 20 Hz to 400 Hz [4] and the known effect of reversible magnetisation was detected as expected (Fig. 9). The amplitude of induced voltages is directly proportional to the magnetising frequency, as shown in equation (2), so the measurements at 20 Hz whereas at 400 Hz the voltages were 20 times higher thus much easier to measure accurately.

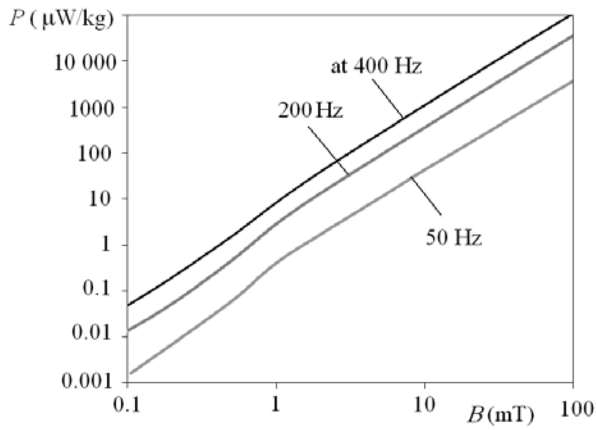

Fig. 10. Power loss curves for GO, 50 Hz

Because the shape of the *B-H* curve is retained it is also possible to calculate its area which is proportional to the magnetic loss. The loss data, corresponding to the measurements shown in Fig. 9, are shown in Fig. 10. The visible inflection points in the loss curves are caused by magnetic behaviour of the material under test and they occur around 2 mT range [1] where the detection of flux density (secondary voltage) is still relatively easy and the noise level it not a substantial problem.

The same method of dithering and averaging was used on different magnetic configurations (toroidal sample) and materials (non-oriented electrical steel and nickel-iron alloys) [1] and in each case measurements at very low flux density were performed as expected for these materials.

4 CONCLUSIONS

The averaging allows digital "suppression" of the noise in the detected signal by a factor $\sqrt{n}$, where n is number of averaged readings. Moreover, if the signal contains sufficient noise (requirement for dithering) the effective resolution of a data acquisition card can be increased. The measurements described here were performed with a 12-bit data acquisition card and it has been detected that the voltage resolution can be improved by several bits with averaging (from up to 10 000 readings). This means that voltages even lower than the card's resolution can be easily detected with enhanced precision.

Acknowledgement

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