MAGNETOMETER WITH A PERMALLOY TRANSDUCER

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Magnetometers with permalloy transducers are widely used for measuring magnetic field strengths of the order of units or tens of oersteds [1-4]. A compensation measuring method is normally used in such instruments. The measured magnetic field $H_x$ is balanced by field $H_b$ of a compensation coil with known parameters. The value of this field is determined from the current which must be transmitted through the compensation coil in order to obtain a complete balance. The permalloy transducer serves only as a null detector for determining the instant of complete compensation.

In measuring stationary magnetic fields, the external field within the transducer is modulated in addition with a low-amplitude alternating magnetic field. In this case the instant of complete compensation can be determined by the symmetry of the emf pulses which are induced in the signal winding during the transducer's alternating magnetization, and by the disappearance of odd harmonics or a maximum number of even harmonics in these pulse trains.

In the instrument described above the measured magnetic field is modulated by a relatively high-frequency sinusoidal field $H_\omega$, which we shall henceforth call a switching field with amplitude $H_0\omega \gg H_c$, where $H_c$ is the coercive force of the permalloy core. When the total field $H_\Sigma = H_x + H_b + H_\omega$ passes through values $\pm H_c$ during period $T_\omega = 2\pi / \omega$, the transducer's magnetic polarity is reversed twice and emf pulses $E(t)$ of different polarities are induced in the signal winding. These pulses are separated by $T_\omega/2$ for $H_\Sigma = H_x + H_b = 0$, or else they are displaced additionally by $\pm \Delta t$, depending on the value and sign of the uncompensated field strength $H'_\Sigma$. For $H_0\omega \gg H_c$, the $E(t)$ pulses are bell-shaped, and their amplitude $V_p$ and duration $\tau$ at level $V_p/2$ can be calculated from the formulas

$$V_p \approx \omega w S_{\mu_{\text{max}}} H_0\omega,$$

$$\tau \approx (0.5 - 1) \frac{B_s}{\mu_{\text{max}} \omega H_0\omega},$$

where $\omega$ is the frequency of the switching field, $w$ is the number of turns in the signal winding, $S$ is the transducer's cross section, $\mu_{\text{max}}$ is the maximum permeability determined by the material and shape of the core, $B_s$ is the saturation induction of the core.

The relationship of displacement $\Delta t$ to the uncompensated field strength $H'_\Sigma$ for $H'_\Sigma \ll H_0\omega$ can be determined from the relationship

$$\Delta t = \frac{2H'_\Sigma}{\omega H_0\omega}. $$

Thus, the train of emf pulses $V(t)$ induced in the signal winding and, therefore, the amplitude of harmonics in this train are a function of $H'_\Sigma$.

Let us determine the first harmonic amplitude of function $V(t)$

$$V_{1p} = \sqrt{a_1^2 + b_1^2},$$

where $a_1$ and $b_1$ are Fourier coefficients represented by the formulas

$$a_1 = \frac{2}{T_\omega} \int_0^{T_\omega} E(t) \cos \omega t \, dt,$$

$$b_1 = \frac{2}{T_\omega} \int_0^{T_\omega} E(t) \sin \omega t \, dt.$$

In order to simplify calculations we shall consider the $E(t)$ pulses to be rectangular with amplitude $V_p$ and duration $\tau$. Such an approximation is fully permissible, since the nature of the relationship of amplitude $V_{1p}$ to $H' \Sigma$ is not affected. The first harmonic amplitude of function $V(t)$ in this case is equal to
\[ V_{1p} = \frac{4}{\pi} V_p \sin \frac{\omega t}{2} \cos \frac{H' \Sigma}{H_{0\omega}} . \] (7)

It will be seen from (7) that $V_{1p}$ has a maximum for $H' \Sigma = 0$. However, it is difficult to establish the instant of complete balance between the measured magnetic field and that of the solenoid by the maximum of the first harmonic of the induced signal train. In fact, although the amplitude of signal $E(t)$ increases with a rising field switching frequency $\omega$, any attempt to increase the transducer's sensitivity only by raising this frequency will not lead to the desired result, since the emf induced in the signal winding by the modulating field will increase simultaneously with $E(t)$. Moreover, the frequency and phase of this stray pickup coincide with those of the useful signal's first harmonic, so that the signal to noise ratio may even drop at a sufficiently high switching field frequency.

In order to separate the useful signal from the pickup the instrument's magnetic field $H' \Sigma$ is modulated in addition at a low frequency with field $H_{\Omega} = H_0 \Omega \sin \Omega t$, with $H_0 \Omega \ll H_{0\omega}$. In this case (7) changes to
\[ V_{1p} = \frac{4}{\pi} V_p \sin \frac{\omega \tau}{2} \left( \frac{H' \Sigma + H_{\Omega} \sin \Omega t}{H_{0\omega}} - \frac{H' \Sigma}{H_{0\omega}} \right) \] (8)

where $V_i$ is the induced amplitude. For small values of $H' \Sigma$ this formula can be converted to
\[ V_{1p} = \frac{4}{\pi} V_p \sin \frac{\omega \tau}{2} \left( 1 - \frac{H' \Sigma}{H_{0\omega}} \sin \Omega t \right) + V_i . \] (9)

It will be seen from (9) that, by using the first harmonic envelope of the pulse train $V(t)$ as the useful signal, it becomes possible to eliminate the effect of induction even for a high switching field frequency. The amplitude detector output signal is equal to
\[ U_d(t) = \frac{4}{\pi} k V_p \frac{H_{\Omega}}{H_{0\omega}} \left| H' \Sigma \right| \sin \frac{\omega t}{2} \sin (\Omega t + \varphi) , \] (10)

where $k$ is the total transmission factor from the signal winding to the output of the amplitude detector and $\varphi = 0$ for $H' \Sigma > 0$ or $\pi$ for $H' \Sigma < 0$. Thus, by adopting a second modulation it becomes possible not only to eliminate the effect of induction, but also to make the signal suitable for phase discrimination.

The block schematic of a magnetometer is shown in Fig. 1. A magnetic field with frequency $\omega = 20 \text{ kHz}$ and amplitude $H_{0\omega} = 27.85 \text{ A/m}$ is used for alternating magnetization of transducer 1. The frequency and amplitude of the low-frequency modulation amounts to $400 \text{ Hz}$ and $1.6 \text{ A/m}$ respectively.

The high-frequency tuned amplifier 3 picks out the first harmonic of $V_p(t)$. The amplitude of pulses $E(t)$ is comparable to that of pickup $V_i$ and amounts to about $20 \text{ mV}$. This amplifier's output signal amplitude is modulated according to (8). Amplitude detector 4 separates envelope $V_d(t)$, and the narrow-band low-frequency amplifier picks out the first harmonic of that envelope and transmits it to phase detector 5. The dc voltage is fed from the detector's output to the pointer null detector 7 for indicating the magnitude and sign of $H' \Sigma$.

In order to facilitate the setting of the required current $I_c$, which flows through the compensating winding, the instrument is provided with a negative feedback circuit. The phase detector output signal is fed to the control input of direct current $I_c$ adjustable source 2. This current is controlled by the voltage drop $V_c = I_c R_c$, which is connected in series with the compensation winding. The value of $R_c$ is selected in such a manner that the value of $V_c$ in volts is recorded on digital voltmeter 9 and corresponds to the tested magnetic field strength in oersteds.

\[ b_1 = \frac{2}{\pi} \int_0^\pi E(t) \sin \omega t \, dt . \] (6)