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COMMUNICATIONS

Generating an AC amplitude magnetic flux density value up to 150 μT at a frequency up to 100 kHz

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AC magnetic field analyzers with a triaxial coil probe are widely used by health and safety professionals, in manufacturing, and in service industries. For traceable calibration of these analyzers, it is important to be able to generate a stable, homogeneous reference AC magnetic flux density (MFD). In this paper, the generating of AC amplitude MFD value of $150\,\mu$T by single-layer Helmholtz type solenoid, described in previous work, was expanded up to a frequency of 100 kHz using the effect of serial resonance. A programmable capacitor array has been developed with a range of adjustable values from 50 pF to 51225 pF. In addition, the multi-layer search coil with a nominal area turns value of $1.3\,\mathrm{m}^2$, used for adjusting AC MFD in the solenoid, has been modified by a transimpedance amplifier for use in a wider frequency range than up to 3 kHz. The possibility of using the programmable capacitor array up to 150 kHz has also been tested. An AC amplitude MFD value of $150\,\mu$T can be generated with expanded uncertainty better than 0.6 % up to 100 kHz.

K e y w o r d s: AC magnetic flux density, serial resonance, Helmholtz coils, search coil, solenoid

1 Introduction

The measurements of AC magnetic flux density are used by health and safety professionals, in manufacturing and in-service industries. Guidelines for human exposure limits have been published by the International Commission on Non-Ionizing Radiation Protection and were updated in 2010 [1]. Based on these guidelines, the EU adopted Directive 2013/35/EU, which sets legal limits for the exposure of humans to magnetic fields. An AC stable and homogeneous magnetic field is needed for traceable calibration of the magnetometers used for measuring these fields. In this work, we have used a single-layer Helmholtz-type solenoid No. 1201 for generating an AC MFD in the range of 3 to 100 kHz, which has been described previously [2]. This solenoid has parameters that match the MFD values set in [1] and, in addition, the design of the solenoid also ensures that the field is homogeneous in the volume of the magnetometer probe [3]. The AC amplitude MFD value that can be achieved with this solenoid is $150\,\mu$T up to 40 kHz, at which the current value is about 1 A, and $30\,\mu$T at a frequency of 100 kHz. Because the impedance of the coil is directly proportional to the frequency, an increasingly higher voltage is needed for higher frequencies. A straightforward solution is to use a high-voltage high-frequency amplifier [4]. However, these devices are not only expensive but also inefficient, because the energy stored in the magnetic field has to be dissipated in every cycle. A serial resonance effect can be exploited to minimize the required voltage range of the amplifier. A programmable capacitor array (PCA) was designed, which was then connected in series with the solenoid to create an LC tank circuit. This enabled us to create an AC amplitude MFD value of $150\,\mu$T even at 150 kHz. Two special search coils were used for measuring the magnetic field. A multi-layer search coil was used for frequencies below 3 kHz and a single-layer search coil for frequencies above 3 kHz. Because the output voltage of the single-layer search coil is very low at low frequencies, we tried to increase the frequency limit of the multi-layer search coil. Instead of voltage, current was measured using a transimpedance amplifier (a current-to-voltage converter), which ensures that the input terminals are being kept at the same potential. This setup almost eliminates the effect of parasitic capacitance of the coil [5, 6].

2 Design and description of the programmable capacitor array

The inductance of the Helmholtz-type solenoid winding was approximately constant, so its reactance grew linearly with frequency. At 150 kHz, its reactance was about $570\,\Omega$ and dominated the impedance, as the equivalent series resistance was only $2.51\,\Omega$. This means that at the required current of 1 A, the power source would have to deliver an RMS voltage of almost 600 V. Instead of using a power source of that type, a PCA (Fig. 1) was designed that was then used to create a series resonant LC circuit.

To achieve an 11-bit range with the lowest number of components, a design of binary-weighted elements was chosen. The binary-weighting means that each subsequent element has the capacity of twice the preceding

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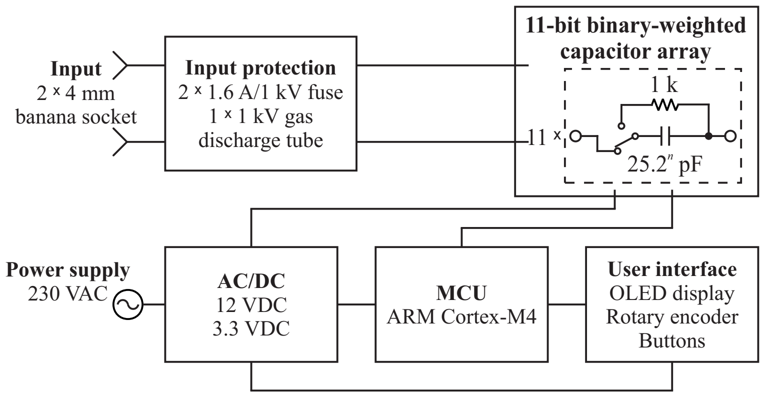

Fig. 1. Schematic diagram of the programmable capacitor array PC1101

element. The maximum (total) capacitance, $C_{\max}$, of a set of N binary-weighted capacitors is

$$C_{\max} = C_0(2^N - 1) + C_p\,, \tag{1}$$

where C_0 is the capacitance of the smallest element, also called the least-significant bit (LSB), and C_p is the parasitic capacitance of the device.

The PCA was designed with 25 pF LSB and 11 bits. The parasitic capacitance was 50 pF, so $C_{\max}$ was 51225 pF. Because the high-voltage capacitors that we chose (Wima FKP1) are not manufactured in linear series, each element (bit) consisted of several capacitors connected together in such a way that the required capacitance would be created. To account for the component tolerances, each bit, with the exceptions of the two LSBs, included a high-voltage mica capacity trimmer (Sprague Goodman GME90201, GME90501 or GME90901). The capacity of each trimmable element was adjusted to its nominal value at 100 kHz using a Hameg HM8118 programmable LCR bridge. The elements were connected in parallel to the input sockets through relays (Finder 40.51). In its disconnected state, each element was shorted by a 1 kΩ resistor to quickly dissipate any stored energy. The switching of the relays was carried out by a Cortex-M4 microprocessor (Atmel ATSAM4S8BA), which accepted input from the user interface. All capacitors were rated for 700 V of AC RMS voltage, and the relays were rated for 400 V of AC RMS voltage for switching with 1 kV (AC) of dielectric strength between open contacts. The input was protected against overvoltage by a gas-discharge tube, and against overcurrent by two 1.6 A high-voltage fuses. We did not use varistors or transient voltage suppressors because of their inherently high parasitic capacitance. The PCA was thus usable for frequencies up to 150 kHz with the Helmholtz-type solenoid.

3 Search coils

Two special search coils with a cylindrical frame and a suppressed octupole were used for the precise adjustment of the AC MFD value in the solenoid. When a search coil is used far below its resonance frequency, it can be considered that the search coil is frequency independent in the described frequency range. The single-layer search coil No. EP 01/00 with a frame made of a material like PTFE and with the calibrated constant $K_{\rm S} = (0.045394 \pm 0.000036)\,{\rm m}^2$ had a resonance frequency value of 3.8 MHz, an inductance value of 38.1 μH and a parasitic capacitance value of 46 pF. A special multi-layer search coil No. $K_{\rm I}$ with a cotton-phenolic laminate (Textit) frame and with the calibrated constant $K_{\rm S} = (1.3312 \pm 0.0011)\,{\rm m}^2$ had a resonance frequency value of 49.6 kHz, an inductance value of 26.3 mH and a parasitic capacitance value of 392 pF. The multi-layer search coil was usable for frequencies up to 3 kHz, while the single-layer search coil was usable in a higher frequency range up to 150 kHz. The measured/set value of $B_{\rm RMS}$ or $B_{\rm m}$ can be calculated from

$$B_{\rm RMS} = \frac{U_{\rm RMS}}{2\pi K_{\rm S} f}\,, \tag{2}$$

$$B_{\rm m} = \frac{U_{\rm AVG}}{4 K_{\rm S} f} \tag{3}$$

where $U_{\rm RMS}$ is the RMS value of the output voltage of the search coil, which we measured using an Agilent 3458 A digital multimeter, $U_{\rm AVG}$ is the mean value of the output voltage of the search coil, which we measured using a Keithley 2001 digital multimeter, $K_{\rm S}$ is the value of the constant of the search coil, and f is the frequency, which we measured with an HP 53131A digital counter. Because the output voltage of the single-layer search coil is very small at lower frequencies – due to the small area turns value – tests were performed to extend the frequency range of the multi-layer search coil. For this purpose, a transimpedance amplifier (a current-to-voltage convertor) was constructed that enabled us to measure the current from the search coil. The input impedance of an ideal transimpedance amplifier is zero, which means that the inputs are held at the same potential, or – in other words – shorted. Our device had an input impedance of 0.11 Ω, which was low enough not to influence the measurement. Shorting the output of the coil reduces the effect of its parasitic capacitance and greatly expands the upper range of usable frequencies. At angular frequencies much larger than the ratio of coil series resistance to coil inductance, the output voltage is independent of frequency [7]. The measured/set value of B_m is then calculated from

$$B_\mathrm{m} = \frac{U_{sc} L_s}{R_z K_s} \tag{4}$$

where U_{SC} is the output voltage of the transimpedance amplifier, L_s is the search coil inductance value, R_Z is the value of the transimpedance gain, and K_S is the value of the constant of the search coil. The core of the transimpedance amplifier consisted of an OPA380 operational amplifier in inverting configuration, with an LM7321 operational amplifier serving as a virtual ground. By using relays, it was possible to switch the gain resistor in the feedback loop between 200, 400 and 4000 Ω. The feedback loop was stabilized by capacitors which, with the feedback resistor, formed a time constant of approximately 8 ns. The relay control through a user interface was provided by an Atmel ATtiny25 microprocessor. Using the transimpedance amplifier, the resonance frequency of the multi-layer search coil was measured and was found to be 405 kHz. The equivalent parasitic capacitance value was then reduced to about 6 pF. This increase should allow the multi-layer search coil to be easily used up to 40 kHz.

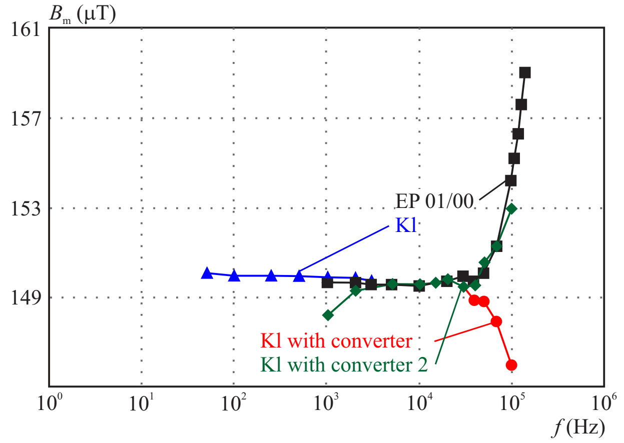

Fig. 2. Measured AC amplitude MFD value for current value of 1 A

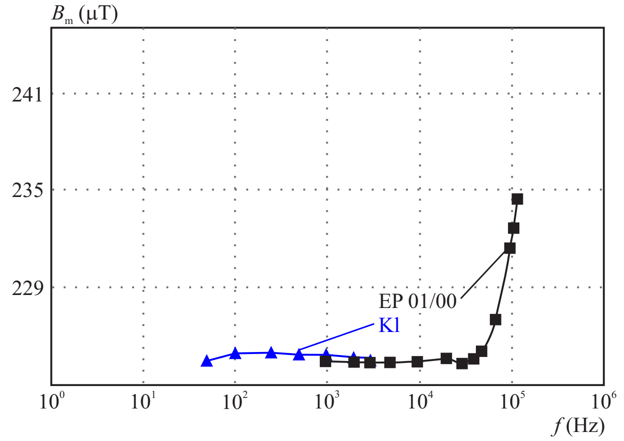

Fig. 3. Measured AC amplitude MFD value for current value of 1.5 A

4 Uncertainty evaluation

The type B relative uncertainty of the measured AC MFD value can be calculated from

$$u_{Bc} = \sqrt{u_f^2 + u_{SC}^2 + u_U^2 + u_d^2 + u_h^2} \tag{5}$$

where u_f is the standard uncertainty of the frequency measurement, u_{SC} is the uncertainty of the search coil constant, u_U is the uncertainty of the search coil (mean or RMS) output voltage measurement, u_d is the uncertainty of the directional dependence measurement of the search coil, and u_h is the uncertainty of the influence of homogeneity inside the MFD in the volume of the search coil. The maximum uncertainty value of the frequency measurement usually varies in tens of ppm, so it can be neglected, because the other uncertainties are typically much higher. The uncertainty of the search coil constant determined by calibration with variable mutual inductance (for search coil No. $\mathrm{K_I}$ and EP 01/00) was 0.04 %. The uncertainty of u_U depends on the digital voltmeter that is used for the RMS voltage value measurements (for a sinusoidal waveform) or for measuring the mean voltage value (for a periodic non-sinusoidal waveform). The value can lie in the order of thousandths to tenths of one percent. The value of u_d can lie in the order of hundredths to tenths of one percent and the value of u_h can be in the order of hundredths to tenths of one percent [8].

The type B relative uncertainty of the measured AC MFD value with the transimpedance amplifier can be calculated as

$$u_{Bta} = \sqrt{u_L^2 + u_{SC}^2 + u_U^2 + u_R^2 + u_{fd}^2} \tag{6}$$

where u_L is the standard uncertainty of the search coil inductance, u_R is the standard uncertainty of the resistor value in the amplifier feedback loop, and u_{fd} is the influence of the distortion in the magnetic field around the search coil produced by measured current. The value of u_L, u_R and u_{fd} can lie in the order of hundredths to tenths of one percent. Standard uncertainty u_{SC} and u_U has the same meaning and value as previously discussed.

5 Measurement results

The generation of an AC amplitude MFD value of 150 μT (resp. the generation of an AC RMS MFD value of 100 μT) was tested using the PCA and multi-layer search coil with a transimpedance amplifier. Measurements were carried out with a sinusoidal waveform up to 150 kHz and for a current value of 1 A and 1.5 A through the solenoid (Figs. 2, 3). The AC amplitude MFD value inside the solenoid can be measured/set up to 150 μT up to 140 kHz or 230 μT up to 120 kHz with expanded uncertainty of (0.2 to 1.0) % for $k = 2$ for the frequencies up to 150 kHz (Table 1).

Table 1. Relative expanded uncertainty (k=2) of the AC amplitude MFD value measured/set in the center of the solenoid

Frequency (kHz)	0.1	3	10	50	100	150
Uncertainty (%)	0.2	0.2	0.25	0.3	0.6	1

Table 2. . Relative expanded uncertainty (k=2) of the AC RMS MFD value measured/set in the center of the solenoid

Frequency (kHz)	0.1	3	10	50	100	150
Uncertainty (%)	0.2	0.2	0.2	0.25	0.3	0.6

An AC amplitude MFD value of 110 μT can be generated at a frequency of 150 kHz for a short time. The AC RMS MFD value can be measured/set with expanded uncertainty of (0.2 to 0.6)% for $k = 2$ (Table 2). The differences of the measured values using the single-layer search coil EP 01/00 compared to the multi-layer search coil K_I were smaller than 0.25 % in the frequency range from 1 kHz to 3 kHz. The frequency dependence of the search coil K_I with the transimpedance amplifier was measured (Fig. 4). Search coil K_I can be used with the transimpedance amplifier from 2 kHz (the search coil corner frequency is 1.2 kHz) up to 30 kHz (the differences from measurements with the EP 01/00 search coil are smaller than 0.28 %) with expanded uncertainty of 0.4 % for $k = 2$. But when we know the frequency dependence, the correction of this dependence can be made. Therefore, these corrections were made for the frequency range of (40–100) kHz and the measurement results are also included in Fig. 4 (KI with converter 2). The differences from measurements with the EP 01/00 search coil are smaller than 0.35 % in the range of (40 up to 70) kHz and smaller than 0.8 % in the range of (70 up to 100) kHz.

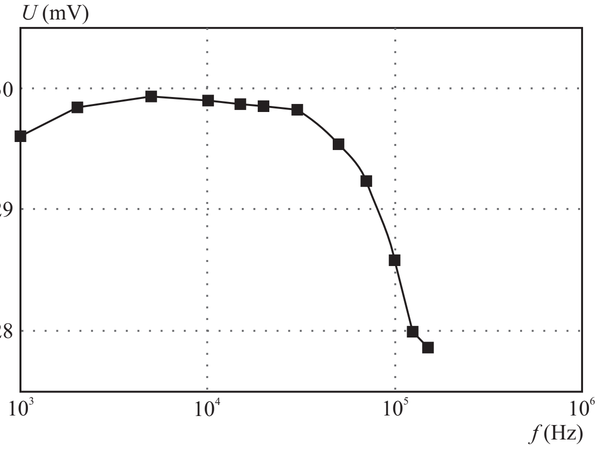

Fig. 4. Frequency dependence of the search coil K_I with the transimpedance amplifier

6 Conclusions

A programmable capacitor array that enables a high-frequency MFD value to be generated in a single-layer Helmholtz-type solenoid with inexpensive low voltage AC power sources has been realized and successfully tested. Specifically, an AC amplitude MFD value up to 150 μT up to 140 kHz and an AC amplitude MFD value up to 220 μT up to 120 kHz can be generated with expanded uncertainty of (0.2 to 1.0) % for $k = 2$. An AC amplitude MFD value of 110 μT at maximum can be generated at a frequency of 150 kHz for a short time. A transimpedance amplifier that expands the upper range of useful frequencies for multi-layer search coils has also been realized and successfully tested. With this amplifier, a part of the frequency range of single-layer and multi-layer search coils conveniently overlaps and allows a large frequency range to be covered with ease, without blind spots. In particular, the differences of measurement with EP 01/00 and with K_I with the transimpedance amplifier were lower than 0.28 % in the overlapping range of 2 kHz to 30 kHz.

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