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THE DESIGN, CONSTRUCTION AND CALIBRATION OF A SYSTEM FOR THE MEASUREMENT OF MAGNETIC FIELDS AT FREQUENCIES IN THE RANGE 20 Hz to 20 kHz

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The design, construction and calibration of a system for the measurement of magnetic fields at frequencies in the range 20 Hz to 20 kHz

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ABSTRACT

A measurement system based on a specially designed pair of Helmholtz coils and associated power supply has been developed for the calibration of magnetic field strength and magnetic flux density measuring instruments covering the frequency range 20 Hz to 20 kHz. The complete system has been calibrated with traceability to NPL electrical standards.

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1 INTRODUCTION

The measurement of low level a.c. magnetic fields has gained prominence in recent years in connection with studies of the effects of ambient a.c. magnetic fields on human health. As a result it was required to extend the well established calibration system used from d.c. to power frequencies upwards in frequency to at least 20 kHz for magnetic flux densities up to 100 μT.

Since most commercial instruments are calibrated in units of magnetic flux density, tesla (T), or more usually one of the submultiples microtesla (μT) or nanotesla (nT), these units are used throughout this report. Moreover, most instruments are calibrated in terms of the rms value of the magnetic flux density. This implies that the calibration of such instruments is only valid for magnetic flux densities of a single value of frequency and with a sinusoidal waveform. The magnetic flux density in air, *B*, can be related to the magnetic field strength, *H*, by the following relationship:

$$B = \mu_r \mu_o H \qquad \textbf{(1)}$$

where: μ_o is the magnetic constant (permeability of free space) = $4 \pi 10^{-7}$ H/m
μ_r is the relative magnetic permeability, taken as unity for air

There were three main parts to the project:

a) the design and construction of a suitable coil system

b) the evaluation and selection of a power supply

and c) the evaluation and calibration of the complete system.

2 DESIGN OF COIL SYSTEM

The heart of a system for the calibration of magnetic field and flux density measuring instruments is a coil system capable of generating a known magnetic flux density which is uniform over the volume of the sensor. Two types of coil system, a long solenoid and a Helmholtz pair of coils, were considered. Some instruments have a Hall effect sensor which is mounted on a handle making it difficult to mount inside a solenoid of reasonable dimensions. Other instruments use a coil type sensor, some of which can be 150 mm in diameter. Again this type of sensor would be difficult to calibrate in a solenoid. A pair of Helmholtz coils offers greater flexibility in the choice of mounting arrangements for the plethora of types of probe likely to be encountered.

For a pair of circular Helmholtz coils the greatest uniformity of magnetic flux density in the central region occurs when the separation of the coils is equal to the mean radius of the windings. Square coils could be used as it is easier to construct the winding formers. In this case the greatest uniformity is obtained when the separation is equal to $\sqrt{(A/\pi)}$ where A is the mean cross sectional area of the winding. In designing a Helmholtz coil system consideration has to be given to the possible maximum size of sensor to be calibrated, the required uniformity of the magnetic flux density over the volume of the sensor and the impedance of the winding at the maximum frequency to be used. The impedance of the coil system needs to be considered in conjunction with the specification of the power supply providing the current through the coils.

A pair of circular coil formers having a diameter of 760 mm and constructed of marine grade plywood were available from a former project. It was calculated that the uniformity over a 150 mm diameter in the central plane would be better than 0.1% (see Appendix). If necessary, a correction could be calculated and applied. For coils of appreciable axial length, a correction is calculated in accordance with a formula derived by Vigoureux[1].

Having established the geometric design, attention was directed to the electrical requirements. To attain a magnetic flux density of 100 μT at a frequency of 20 kHz there is necessarily a compromise between the level of the magnetizing current, the number of turns and the impedance of the windings. The magnetic flux density in a circular Helmholtz coil system is given by:

$$B = \frac{8 \mu_r \mu_o \, N \, I}{5\sqrt{5}\, r} \qquad (2)$$

where: B is the magnetic flux density, in tesla
N is the number of turns on each of the two coils
I is the current flowing in the Helmholtz coils, in amps
μ_o is the magnetic constant (permeability of free space) = $4 \pi 10^{-7}$ H/m
μ_r is the relative magnetic permeability, taken as unity for air
r is the mean radius of the windings, in metres

In order to minimise the inductance of the coil, and hence its impedance at high frequencies, the windings comprised 4 turns per coil of mean radius 380 mm. For a magnetic flux density of 100 μT a current of 10.6 A is required. The windings comprised a multistranded conductor formed from Litz wire in order to obtain a flexible conductor capable of carrying the required current with no significant heating and to minimise skin effects at the higher end of the frequency range.

The conductor was made up of 9 strands of 27 x 0.061 mm double silk covered Litz wire. An ordered conductor was obtained by firstly producing two circular acrylic plates each having nine 2 mm diameter holes drilled in a regular circular pattern on a diameter of approximately 40 mm. The strands of wire were cut about 20% greater in length than required and carefully laid out in a long passageway. Each end of each strand of wire was threaded through corresponding holes in the circular plates, care being taken to ensure the conductors did not cross and were parallel to each other. The ends were then bunched together and clamped in the chucks of two twist drills, one at each end. With an operator at each end a controlled number of turns were made, the same number from each end, thus producing a well ordered twisted cable. Three lengths of cable were produced and the process repeated using only three of the holes in each spacer, the holes being chosen to be equally spaced. The final cable thus comprised 27 strands of 27 x 0.061 mm diameter double silk covered copper Litz wire. The total cross sectional area of the wire was calculated to be 2.13 mm^2.

If necessary, the interwinding capacitance could have been further reduced by spacing the four turns (wound in two layers of two) using a cruciform shaped flexible spacer. This option may be added if measurements at higher frequencies are required.

The real and imagninary components of the impedance of the total winding of the two coils in series were measured at a number of frequencies up to 100 kHz. The magnitude of the impedance at 20 kHz was found to be approximately 12 Ω. This value of impedance together with a required current of the order of 10 A seemed to be within the limitations of possible power supplies. This being so the windings were carefully terminated and the two coils permanently connected in series addition. The leads between the coils and the supply leads were carefully twisted to avoid inductive loops which would affect the uniformity of the magnetic field within the coils. The supply leads comprised a twisted pair of PTFE insulated wires. PVC insulated cable was used at first but the losses due to the poor dielectric constant of this material appeared to be significant above a few kHz.

3 POWER SUPPLY

The power supply is required to meet the following conditions simultaneously:

- to provide a current of up to 11 A into an inductive load of impedance approximately 12 Ω at a frequency of 20 kHz

- the current waveform is to be sinusoidal, with a distortion of less than 0.2 %.

Experiments with an existing Amcrom M-600 power supply revealed that its maximum output voltage of 70 Vrms was a limitation. A literature survey of power supplies in current production showed that it would be possible to use two Techron 7700 amplifiers in series mode to provide the required voltage range of approximately 140 V. With this arrangement of this particular type of amplifier it is possible to earth one end of the combined outputs.

The two power supplies were connected through an opto-isolator circuit such that one amplifier was used as the master and the other as a slave. Initial measurements on the amplifiers were made to determine the levels of distortion of the current and voltage waveforms under working conditions, using a calibrated distortion meter. At frequencies up to 20 kHz the distortion of the current waveform was found to between 0.01 % and 0.2 %, depending on the frequency and current level. This was within the required distortion level of the current waveform of 0.2 %. The results are given in table 1.

Table 1. Distortion measurements on Techron 7700 amplifier system.

current (A)	distortion (%) at a frequency of (Hz)						
	50	400	1 000	5 000	10 000	15 000	20 000
2.5	0.10	0.024	0.018	0.025	0.059	0.071	0.083
5.0	0.20	0.065	0.017	0.013	0.024	0.035	0.048
7.5	0.12	0.110	0.016	0.010	0.017	0.025	0.044
10.6	0.09	0.011	0.044	0.010	0.015	0.026	0.062

4 LOW FREQUENCY CALIBRATION OF HELMHOLTZ COILS

The magnetic field strength to current ratio of the Helmholtz coil system was determined at a frequency of 20 Hz using the mutual inductance comparison bridge shown in figure 1. The bridge is energised at a low frequency in order to avoid the effects of capacitance in the mutual inductor windings. The mutual inductance between a standard search coil and the Helmholtz coils is balanced by a calibrated variable mutual inductor. The magnetic field strength to current ratio, *H/I*, is then given by:

$$\frac{H}{I} = \frac{M}{\mu_r \mu_o N A} \qquad \text{(A/m/A)} \qquad \textbf{(3)}$$

where:
M is the mutual inductance, in henries
μ_o is the magnetic constant (permeability of free space) = $4 \pi \, 10^{-7}$ H/m
μ_r is the relative magnetic permeability, taken as unity for air
NA is the effective area of the search coil, in square metres

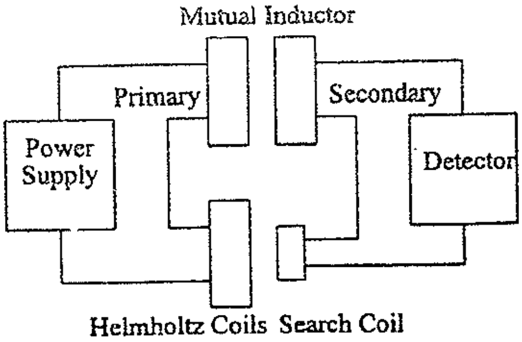

Figure 1 Mutual inductance comparison bridge

A search coil with an effective area turns product of approximately 16 m^2 was used in the calibration of the Helmholtz coils. This coil was calibrated using the same circuit as in figure 1 by comparison with a standard search coil in a low frequency high field Helmholtz coil system.

The standard search coil comprises a precisely machined cylinder of fused silica on which a single layer winding of bare copper wire is wound under tension with air spacing between turns. The effective area x turns product of the coil is determined from the number of turns and the mean diameter of a turn. The latter was calculated from metrological measurements of the diameter of the coil former and the overall diameter of the winding. The *H/I* ratio was found to be 7.510 A/m/A with an uncertainty of less than 0.35 %.

5 HIGH FREQUENCY CALIBRATION OF HELMHOLTZ COILS

At frequencies in the range 40 Hz to 20 kHz the calibration was achieved by measuring the voltage output of a calibrated search coil mounted at the centre of the Helmholtz coil system. The basic circuit is given in figure 2.

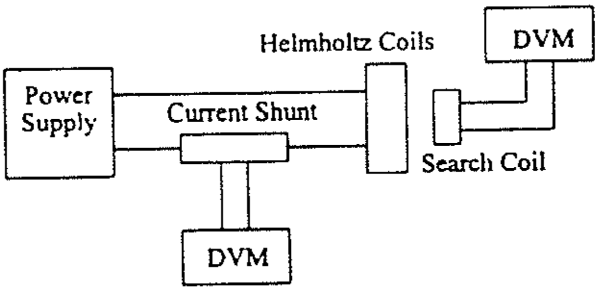

Figure 2 Calibration circuit for frequencies in the range 40 Hz to 20 kHz

A number of precautions were necessary, particularly at frequencies above 1 kHz, to ensure that the effects of capacitances in connecting leads, search coil, input circuit of the digital multimeter and time constant of the current measuring resistor all had negligible effect on the measurement up to a frequency of 20 kHz. At the higher end of the frequency range the effect of the capacitance of the windings of the Helmholtz coils and the input impedance of the digital multimeters needed to be taken into account.

6 MEASUREMENT ENVIRONMENT

Since the Helmholtz coil system is to be used in the calibration of low magnetic flux density measuring instruments, it was necessary to explore the levels of the ambient ac magnetic flux densities in various possible areas where measurements might be carried out.

Measurements were made using a commercial instrument, an NPL calibrated Combinova MFM 10 on temporary loan, in the main Magnetics Laboratory, room 112 building 5 and in the screened room in room 023 of building 5 and in the low magnetic field laboratory in room 25 Building 1. The results are reported in table 3.

Table 3. Measurement of ambient ac magnetic flux densities

building	room	area	flux density (nT)	frequency (Hz)
1	25	all parts of floor to 1 m above floor	0	noise
1	8/9	corridor outside rooms	68	50
5	023	near door outside screened room	68	50
5	023	near trunking in main room	53	50
5	023	centre of floor of screened room, tungsten lights off	8	noise
5	023	as above, lights on	8	noise
5	023	screened room, bench near powered equipment	84-128	50
5	023	main room, desk by powered transconductance amplifier	1 980	50
5	023	as above, amplifier off	67	50
5	112	NE corner, bench height	48	50
5	112	NW corner, bench height	15	50
5	112	SW corner, bench height	68	50

As a result of this investigation the measurement system was transferred to the Low Magnetic Field Laboratory. It was thought that the very low ambient ac magnetic flux density level detected in this laboratory was due to the complete absence of metalwork in the structure of the room and surrounding areas together with the remoteness from electrical supplies and interfering signals generated within NPL.

7 CONCLUSIONS

A complete system for the measurement of magnetic fields at frequencies in the range 20 Hz to 20 kHz at magnetic flux densities up to 100 μT has been designed, constructed and calibrated.

8 REFERENCE

1 *NPL Report DES 130, Formulae for the calculation of the magnetic field strength in a Helmholtz coil system with circular coils. P. Vigoureux, December 1993.*

APPENDIX

Calculation of the uniformity of the magnetic flux density in the central plane of a Helmholtz Coil System.

Since, in practice search coils associated with flux density measuring instruments have diameters of up to 15 cm or more it is necessary to calculate the radial variation of the magnetic flux density in the central plane of the Helmholtz Coil System to be used. This variation takes the form:

$$B = B_0(1 - CR^4) \qquad \textbf{(A1)}$$

where:
B is the axial magnetic flux density
B_0 is the axial magnetic flux density at the centre of the coil system
R is the radial distance from the centre of the coil system
C is a constant

The formula, derived by Vigoureux[1], which gives us the form of the above relationship enables us to plot a graph of the radial variation of the axial magnetic flux density for our coil system, see figure A1 below, and obtain a value for C above.

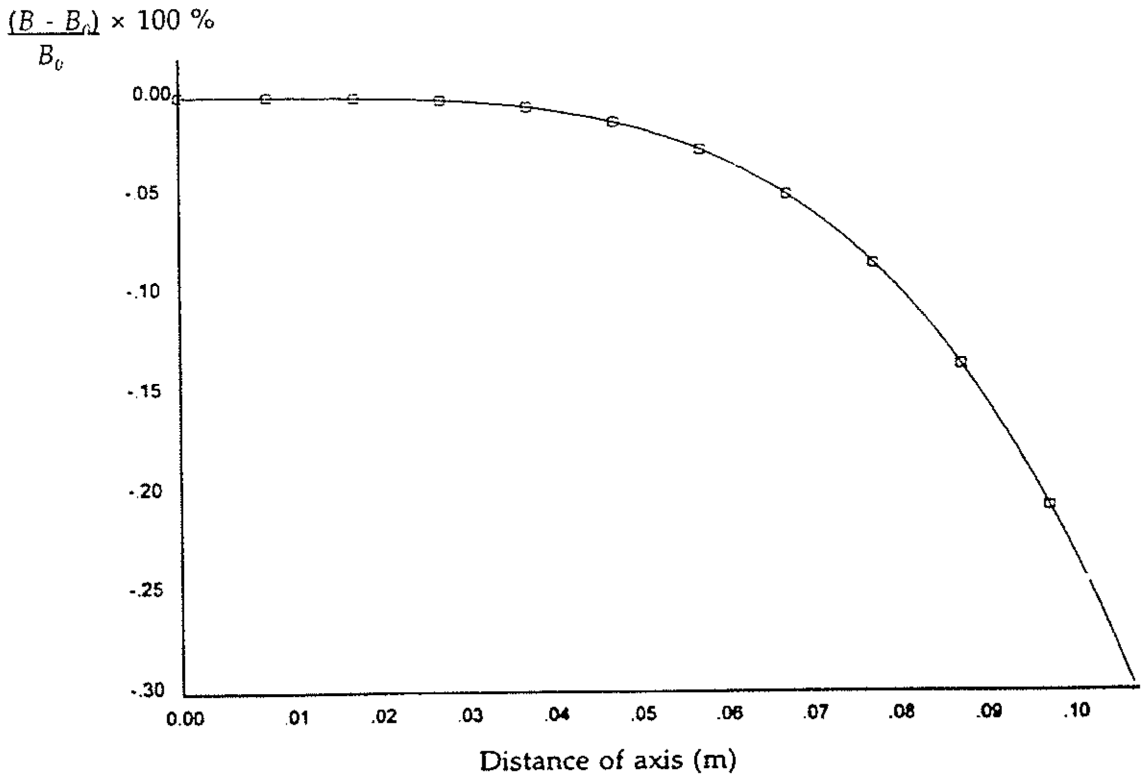

Figure A1 Radial field variation from centre of Helmholtz Coil System M108

We are now able to apply a correction for the radial variation of the field in the coil system for a particular diameter of sensor, d. The sensor performs an integration of the magnetic flux density over its area:

$$B_{TOT} = \frac{1}{\pi\left(\frac{d}{2}\right)^2} \int_0^{\frac{d}{2}} B \, 2\pi R \, dR \tag{A2}$$

But, since we know the form of B over this area we may also perform this integration and obtain a value for B_{TOT} (the average value over the area of the sensor), which will be less than B_0 (the value at the centre). The correction then simply takes the form of a multiplication by B_0/B_{TOT}.