

TRACEABLE MAGNETIC FIELD STRENGTH MEASUREMENTS IN THE FREQUENCY RANGE DC TO 120 kHz.

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Introduction

The calibration of coil systems and instruments which measure magnetic fields is not a new requirement. However, following recent reports which have appeared on studies of the effects of magnetic fields on human health, there has been a marked increase in the demand for the calibration of such instruments particularly at power frequencies and above. In addition, there are requirements from the defence and aerospace industries for the calibration of DC magnetic fields and sensors at sub-nanotesla levels. To meet these ongoing needs traceable measurement systems have been established at NPL for low level magnetic field measurements up to a frequency of 120 kHz.

These measurements systems have been set up in a specially prepared low magnetic field facility. The facility includes a large triaxial Helmholtz coil with a servo system for ambient field cancellation and a single axis Helmholtz coil designed for high frequency operation.

Low magnetic field facility

In setting up such a facility a prime consideration must be the ambient level of the magnetic field and its gradient. A room was chosen in Bushy House (where NPL was founded) which had two intrinsic advantages. Firstly, the building itself is situated at a relatively remote end of the Teddington site away from other buildings - the room being at the remotest end of the building. Secondly, Bushy House was built at a time before the use of steel girders etc.; in fact, there is no metal in the construction of the room at all. This has advantages for both the magnetic field level and gradient in the room and also the pick-up and re-radiation of magnetic fields associated with steel framed buildings.

To establish the DC gradient in the room, surveys were carried out at points on a 1 m square grid over the room at two heights of 30 cm and 2 m (the latter being approximately the height of the centre of the proposed triaxial Helmholtz coil system). The initial surveys indicated two main areas of high localized DC magnetic field gradient: in the floor of the room where the coil was probably to be situated and along one wall. These and other smaller disturbances were located more accurately using a commercial metal detector and removed. Most of the ferromagnetic material was made up of small pieces set into the concrete floor together with a reinforcing grid six foot square set two feet deep into the concrete. Once this material had been removed, the magnetic field gradient across the room was found to be reduced from about 200 nT/m (and >1000 nT/m in localized regions) to a relatively uniform 15 nT/m overall.

The room was then fitted out with non-magnetic materials i.e. wooden benches, aluminium radiators fed by nylon pipe and brass door and light fittings.

Magnetic environment

The DC magnetic field in the room was measured in three orthogonal directions (North-South, East-West and Vertical) using a triaxial fluxgate magnetometer. The major contributions to variations in the ambient magnetic field were from magnetic storms giving variations of the order of 100 nT, a slow diurnal variation of 100 to 200 nT peak to peak, thought to be due to the effect of the sun on the ionosphere¹, and rapid changes due to electric train services. The latter are the most apparent perturbations on the NPL site having typical amplitudes of 50 to 100 nT over periods of approximately 1 minute at intervals of several minutes. The effects are caused by there being two railway stations approximately 2 km apart with NPL in between. The electric trains operate on a DC supply, the return current flows through the running rails and leaks into the ground resulting in disturbances predominantly in the vertical magnetic field but which are significant in the horizontal components also.

The ambient AC magnetic field has also been investigated. The level measured in the low magnetic field facility was below 1 nT whereas in other rooms and buildings on the NPL site the average was about 50 nT.

DC triaxial Helmholtz coil system

Construction The object of the triaxial Helmholtz coil system was to produce an area of magnetic field uniform to ± 0.1 nT over a 15 cm cube. The approach to this was to cancel out the ambient magnetic field using such a coil system in conjunction with a remote sensor and to use separate windings to produce a uniform field in one axis only. To achieve a magnetic field uniform to ± 0.1 nT over a 15 cm cube requires a circular Helmholtz coil system, which for constructional and space considerations was limited to 3 m in diameter together with subsidiary coils of diameter 0.5 m. Using the main coils alone the required uniformity can be achieved over a 14 cm cube.

To construct the coil system, a material needed to be found that was both stable enough to be able to be made into a structure of that size, with tight dimensional tolerances and also with a high enough strength to weight ratio so that it didn't sag under its own weight. A major requirement was that it had to be non-magnetic and non-conducting (so as not to produce eddy currents that affect the field produced). A material (Fibrelem) was found that met all these requirements. It is made from resin bonded honeycomb paper sandwiched between laminated paper sheets. The honeycomb may be filled at the edges to allow the structure to be machined for the production of grooves etc. The whole structure was made from sections glued together and oriented using tooling designed specifically to ensure orthogonality between axes and parallelity and the correct separation between pairs of coils to within 0.5 mm.

Servo system In deciding on a strategy for the cancellation system, the uses to which the system were to be put had to be considered. One such use is to calibrate magnetic field measuring devices, for which an applied field is required, another is the measurement of the magnetic field strength at a specified distance from an object and thirdly to calibrate other coil systems using a proton resonance magnetometer. All of these requirements are not possible or at least much more complicated, if a closed loop feedback system is used. It is also hard to see how to position the sensor so that it doesn't interfere with the device under test.

The system adopted is an open loop cancellation system. A remote triaxial fluxgate sensor is located in the garden of Bushy House approximately 60 m from the coil system (this being sufficiently far away from the coil system that magnetic field changes produced by it are not seen by the sensor). Signals from the remote sensor are used to control the currents supplied to the corresponding axis of the coil system. There are however, some inherent drawbacks with this type of approach. Firstly, the system depends on the variations in the ambient magnetic field in the garden and in the room being the same (or at least constantly proportional). Secondly, the remote sensor needs to be carefully aligned with the coil system. Both the above will ultimately limit the cancellation ability of the system - the former probably being the most significant.

Calibration The separate windings on one axis of the triaxial Helmholtz coil system were calibrated using a proton resonance magnetometer giving traceability to the standard of frequency and the gyromagnetic ratio of the proton. The method used was to set up the cancellation system in all three axes to null the magnetic field to as near to zero as possible (as measured using a second triaxial fluxgate magnetometer) at the centre of the coil system. The triaxial sensor was then removed and replaced by the proton resonance magnetometer. A measured current was passed through the additional pair of windings on the East-West axis former (designed for the application of magnetic fields) and several readings of the proton resonance magnetometer taken. The current was then reversed and another series of readings taken. Finally, the proton resonance magnetometer was replaced by the triaxial sensor after the applied current had been switched off and the drift from zero of the cancelled field estimated. From the measurement of the currents and the readings of the proton resonance magnetometer the magnetic field strength to current ratio of the additional windings was calculated.

Using this calibration value it is then possible to calibrate magnetic field measuring devices with a resolution of better than 1 nT. Also, using the same technique as has been described for the calibration of the additional coils of the triaxial coil system other coil systems including solenoids can be calibrated, provided that they can be located inside the triaxial coil system.

AC high frequency Helmholtz coil system

Construction The requirement to perform calibrations at frequencies up to 120 kHz presents several new problems not encountered with power frequency calibrations. At these frequencies the impedance of coil systems (due to their self-inductance) is much higher than at 50 Hz. It is, of course, possible to reduce the number of turns on each winding, but then a higher current is required for a given magnetic field strength. A compromise has to be made between turns and current so the Helmholtz coil system which was used for this work has circular formers of 0.8 m in diameter with 4 turns on each.

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 minimize skin effects at the higher end of the frequency range. The conductor was made from 27×0.061 mm double silk covered Litz wire. Firstly, nine strands of this were carefully twisted together in an orderly way to form a cable 20 % longer than was required. Three lengths of cable were produced in this way and were in turn twisted together to form the final cable consisting of 27 strands of 27×0.061 mm double silk covered Litz wire having a total cross-sectional area of 2.13 mm^2 .

The coil system is supplied by a pair of amplifiers in series mode capable of producing an output voltage in excess of 150 volts. The original design specification for this project was to be able to produce 0.1 mT at 20 kHz (this requires that the power supplies provide approximately 10 amps with an output voltage of approximately 120 volts).

Calibration The Helmholtz coil system is calibrated at a particular frequency by determining the ratio of the magnetic field strength developed at the centre of the coil system to the current flowing in it. The coil current is measured using a precision high frequency resistor. The magnetic field strength is measured using a search coil aligned coaxially at the centre of the coil system. The voltage, V_{rms} , induced in the search coil is related to the magnetic field strength at the centre of the coil system, H_{rms} , by the following equation:

$$V_{rms} = 2\pi f \mu_0 H_{rms} AN$$

where f is the frequency of the alternating magnetic field, μ_0 is the permeability of free space and AN is the effective area turns product of the search coil.

The search coil was specially designed and is made from a single layer winding of spaced bare copper wire on a PTFE former to minimise capacitance and dielectric loss effects at high frequencies. Also, the effect of the input impedance of the DVMs used to measure the voltage developed across the resistor and that induced in the search coil also need to be ascertained at the frequency used.

Conclusion

A low magnetic field facility and two measurement systems have been set up for the calibration of magnetic instruments and coil systems in the frequency range DC to 120 kHz for low magnetic fields. When fully operational a triaxial Helmholtz coil system will enable DC measurements to be made to sub-nanotesla levels with a corresponding uniformity over a 15 cm cube. In a separate system, AC magnetic instruments will be calibrated at any frequency up to 120 kHz with significant improvements in uncertainty over existing techniques (TEMS Cell)².

References

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- [2] Crawford, M L, "Generation of standard EM fields using TEM transmission cells", Trans. Inst. Electr. Electron. Eng. EMC, 16(4), pp. 189-195, 1974.