Proceedings

2nd IMEKO TC 11 International Symposium METROLOGICAL INFRASTRUCTURE
June 15-17, 2011, Cavtat, Dubrovnik Riviera, Croatia

PREPARATION OF THE NATIONAL MAGNETIC FIELD STANDARD IN CROATIA

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Abstract −The rationale for, and the way of preparation of the croatian national standard for low frequency magnetic field are presented. The technical characteristics of the system for the reference magnetic field generation are described. The calculation of the reference field nonuniformity and the expression of the reference field generation uncertainty are presented, and the experience with the preliminary use of the system for the magnetic field-meters calibration is described.

Keywords: magnetic field, standard, calibration, uncertainty.

1. INTRODUCTION

As a consequence of growing public concern regarding the possible adverse health effects of low frequency magnetic fields, the national and international protective legislation prescribes measurement and control of field levels in human environment. The magnetic field-meters used for such legal metrology have to be calibrated regularly.

Calibration of magnetic field meters requires magnetic field standard that generate reference magnetic fields of high uniformity (in continuation of the paper this standard will be called a *reference*). Such reference magnetic fields are generated by specially constructed reference coils.

Magnetic fields generated by the reference coils are not completely uniform, and the field nonuniformity contributes to the overall calibration uncertainty. The maximal permitted level of the reference field nonuniformity is recommended by international standards [1, 2], where some reference coils constructions are recommended as well.

For realization of our reference magnetic field, the standard square loop reference coil has been used. The coil has been carefuly constructed and build, bearing in mind that coil construction parameters influence, not only the reference field uniformity, but also the coil electrical characteristics. Reference coil electrical characteristics, as resistance and inductance, are important for sizing and construction of the power supply needed for the reference system realization.

For realization of the national magnetic field reference, the calculation of the reference field uncertainty is of utmost importance. For that purpose the reference field nonuniformity has been calculated, using the numerical field calculation [3].

Finally, the constructed magnetic field reference system has been tested in calibration of 5 different field-meters. The procedure and results of this calibration are described at the end of the paper.

2. REFERENCE SYSTEM CONSTRUCTION

Calibration of a magnetic field-meter is normally done by introducing the field-meter probe into a nearly uniform reference magnetic field of known magnitude, direction and waveform.

While DC magnetic field-meters, with small Hall-effect probes, can be calibrated in the narrow space of a reference field generated by permanent magnet, for calibration of AC field-meters, with larger, inductive (coil) probes, the reference fields with larger area of uniformity are needed. For generation of such reference fields, systems with large reference coils are used. Such kind of reference system has been constructed at the Faculty for Electrical Engineering and Computing the University of Zagreb.

The magnetic field reference system is generally functioning so that electric current of known strength is let to flow through the windings of the reference coil, generating the magnetic field of the known strength at the centre of the coil, where the probe is put for calibration.

A basic schematic view of a circuit for reference magnetic field generation (taken from [1]) is presented in Fig 1.
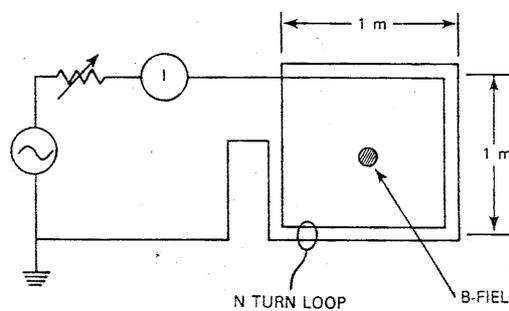

Fig. 1. Schematic of circuit for reference field generation

During calibration, the probe is placed in the central area of the reference coil where the field has highest uniformity.

At the centre of the reference coil, the magnetic flux density B is proportional to the current strength I. Factor of proportionality depends upon the shape and dimensions of the reference coil, and can be calculated. By means of this coil factor, for any current strength I, magnetic flux density B at the centre of the coil can be determined.

The main components of such a system for reference magnetic field generation are: power supply, an instrument for current measurement, and a reference coil.

While a stabile power-supply, and precise ampermeter are standard components that can be generally found, the reference coil is a special component that contributes the most to reference system uncertainty. Therefore, construction of the reference coil is of special importance.

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2.1. Reference coil construction

For reference field generation, a square form of reference coil has been used, as it is proposed in international standards [1, 2]. To achieve high field uniformity in the coil central volume, where the probe is put for calibration, the 1 m wide reference coil configuration has been used.

The shape and size of the reference coil configuration is presented in Fig.2. This configuration has a square coil with *N*=200 turns, arranged in 5 layers, each with 40 turns of thickness *d*=1,1 mm.

According to [2], the (inner) side dimension of the inner layer turn is 2*a*=1 m. This coil (winding) length is *l*=4,4 cm, and the winding width (thickness) is *w*=0,55 cm, as presented in Fig. 2.
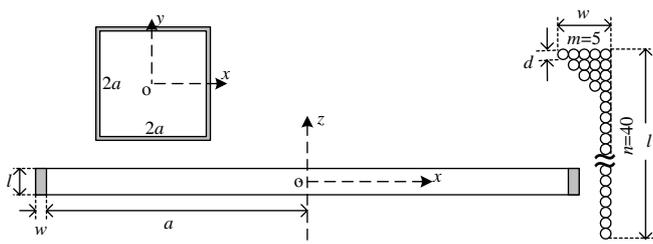

Fig. 2. Shape and dimensions of the reference coil

In Fig. 2 the plan view, side view, and the cross-section of the reference coil are drawn. To fit together, three coil drawings are presented with different scaling.

Knowing the presented shape and dimensions of the reference coil enables us to calculate the reference field for the given current strength.

2.2. Reference field calculation

For calculation of the magnetic flux density *B* at the centre of a square current loop, we can use a simple formula (based upon the Biot-Savart law)

$$B_0 = \frac{\mu_0 \, IN\sqrt{2}}{\pi \, a} \ . \qquad (1)$$

where *I* is current strength, *N* is number of turns, and 2*a* is dimension of the square loop side.

From (1) we can see that reference field level is inversely proportional to the coil side dimension *a*. Thus, recommendation for larger coil dimensions means the requirement for stronger current source, what complicates the calibration system realization.

However, expression (1) can be used only for approximate field calculation, because it approximates current loop with a line without dimension, i.e. it does not take in account the thickness of the current loop. In such, idealised case, all the current would be in one layer, and without any thickness.

In case of a real coil, where each turn represents separate current loop, the situation is more complicated. As we can see from the Fig. 2, our coil turns are not in the same layer, and also they have different distances from the coil axes.

All turns do not have the common centre point, and the field level at each point should generally be calculated as a vector sum of contributions of all *N* turns.

Therefore, our multilayer coil requires more accurate field calculation than the one enabled by expression (1). For an accurate calculation of the magnetic flux density at any point in the field generated by the reference coil with winding of *N* turns, the winding spatial arrangement, i.e., the exact position of each turn should be considered.

General geometry for such field calculation is presented in Fig. 3. Current loop in Fig. 3 represents one rectangle turn, with the point P for field calculation dislocated from the turn centre.
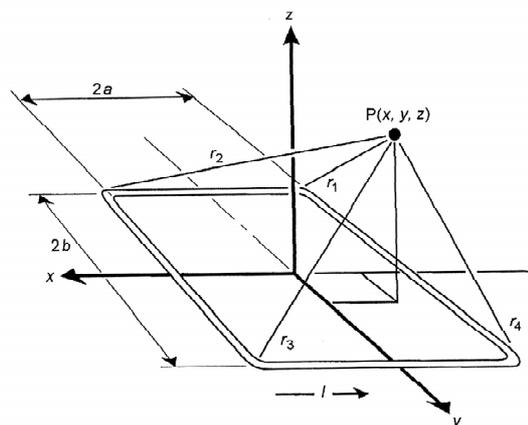

Fig. 3. Geometry for calculation of rectangular coil field

Based upon the Biot-Savart law, the field z-component B_z (axial field) produced by a rectangular current loop *I* at the point P(x,y,z), as shown in Fig. 3, can be expressed as:

$$B_z = \frac{\mu_0 \, IN}{4\pi} \sum_{k=1}^{4} \left[\frac{(-1)^k d_k}{r_k [r_k + (-1)^{k+1} C_k]} - \frac{C_k}{r_k (r_k + d_k)} \right]. \qquad (2)$$

where: $C_1 = -C_4 = a+x$; $C_2 = -C_3 = a-x$;
and $d_1 = d_2 = b+y$; $d_3 = d_4 = y-b$.

This is a general expression for a rectangular loop field, which in case of a square loop is simplified by *b*=*a*.

According to [1, 2], only the field z-component B_z is of our interest, because only this (axial) field component, which is parallel to the coil axes, effects the meter reading during calibration.

By addition of partial contributions of each of *N* turns, calculated by means of (2), an accurate calculation of axial field at any point can be performed. That can enable a detailed analysis of magnetic field produced by the reference coil. This analysis is necessary to determine the field nonuniformity , which is the main source of the reference system uncertainty.

3. REFERENCE SYSTEM UNCERTAINY

The reference field nonuniformity strongly influences the uncertainty of reference field generation, which is the main component of the calibration system uncertainty.

To keep the calibration uncertainty low, the reference field nonuniformity in the probe area, according to [2], should not exceed 1 %.

By means of (2) field calculation around the coil centre was used to quantify our reference field nonuniformity.

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2ⁿᵈ IMEKO TC 11 International Symposium METROLOGICAL INFRASTRUCTURE
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2.1. Reference field nonuniformity

The field nonuniformity at some point in the field is a measure of the departure of the axial field level B_z at that point from the field level B_0 at the centre of the coil. Expressed as a percentage, it can be calculated as:

$$n = \frac{B_z - B_0}{B_0} \cdot 100 \ . \qquad (3)$$

The field level changes while moving from the centre of the coil system along the coil axes (z-axes). The magnitude of that change characterizes the longitudinal uniformity of the reference field.

Field calculation is showing that field level decreases with the longitudinal distance from the centre of the coil (in longitudinal direction) as presented in FIg. 4.
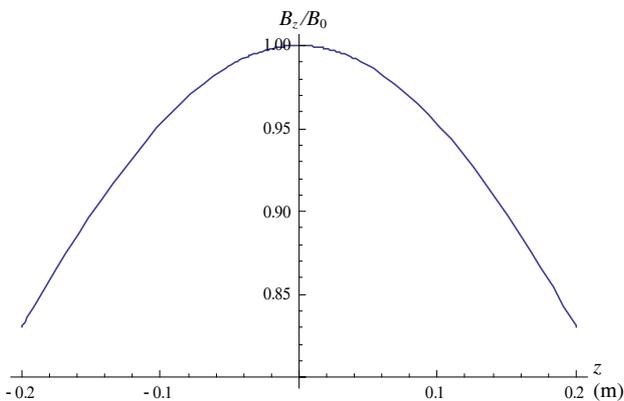

Fig. 4. Longitudinal uniformity of the reference field

At the other side, field calculation is showing that field level decreases with the transversal distance from the centre of the coil (in transversal direction) as presented in FIg. 5.
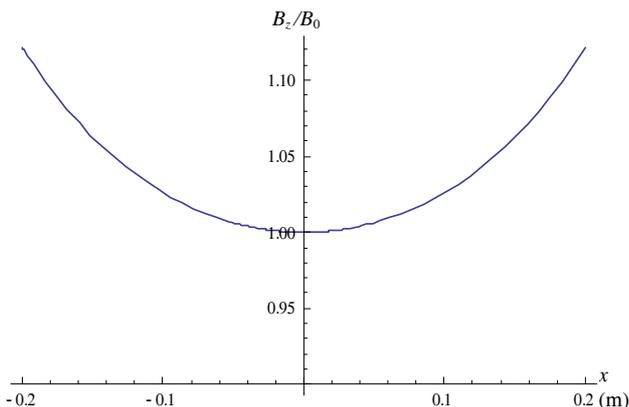

Fig. 5. Transversal uniformity of the reference field

A view on Fig. 4 and Fig. 5 indicates important fact that, concerning the effect of the field nonuniformity on the field-meter reading during calibration, errors with probe positioning in longitudinal and transversal direction mutually compensate. We can see also, that transversal nonuniformity is slightly lower than the longitudinal.

This means that a higher error margin is allowed in transversal positioning of the probe. That is convenient; because the longitudinal positioning is easier (one has only to align the planes of the probe and the reference coil).

To get some quantitative indicators, the exact values of the field nonuniformity have been calculated for several points displaced from the coil centre in longitudinal, as well as in the transversal direction, Results are presented in tables I and II.

TABLE I. Calculated field nonuniformity n along the z-axis

	Distance from the centre (0;0;0) cm		
Displacement	1 (0;0;1)	3 (0;0;3)	5 (0;0;5)
n %	-0,049	-0,444	-1,226

TABLE II. Calculated field nonuniformity n along the x-axis

	Distance from the centre (0;0;0) cm		
Displacement	5 (5;0;0)	7 (7;0;0)	10 (10;0;0)
n %	0,633	1,254	2,620

The actual field-meter probes have usually the shape of round coil with diameter to 0,1 m. During calibration, the probe is placed in the reference coil centre, so that planes and axes of these two coils coincide.

Results of field calculation, presented in tables I and II, perfectly match the results from [2] where the largest departure of magnetic field from the central value, for the 0,1 m diameter probe, is declared to be 063%. The difference of 0,003% comes from the fact that in [2] the central field value was calculated by means of (1).

It is noteworthy that a field-meter with a coil probe indicates a magnetic field value that is an average of the cross-sectional area of the probe, and the difference between this average and the central value will be less than the maximum percentage departure from the central value. In case of the 0,1 m coil probe, the average field is only 0,31 % more than the central (calibration field) value.

Moreover, if the shape and dimensions of the probe are known, presented accurate field calculation gives a possibility to determine the actual average field value in the probe area. That enables the full compensation for the reference field nonuniformity, thus eliminating the contribution of field nonuniformity to the uncertainty of the reference field generation.

2.2. Uncertainty of the reference field generation

Beside the uncertainty component due to the field nonuniformity u_n, the uncertainty of the reference field generation u_B is influenced by the uncertainty of the current strength measurement u_c, as well as the uncertainty of the reference coil dimensioning u_d (which reflects the possible influence of imprecision in coil dimensioning).

According to [2], the uncertainty of the reference field generation u_B can be calculated as a combined uncertainty of these three components:

$$u_B = \sqrt{u_n{}^2 + u_c{}^2 + u_d{}^2} \qquad (4)$$

Taking the worst case of 0,633 field nonuniformity as an error margin in a rectangular distribution (so that it includes eventual errors in probe positioning) gives an uncertainty due to field nonuniformity of the value u_n=0,37 (coverage factor 1).

The uncertainty of current measurement u_c depends upon the stability of power supply and the precision of the instrument used for current measurement. In our reference system we use a stabilized power source and precise measuring instrument, so that error margins of current measurement are within ±0,1 %. That results in the uncertainty value u_c=0,058 (coverage factor 1).

Measurement of the realized reference coil dimensions have shown a high precision of coil manufacturing, so that the uncertainty of the reference coil dimensioning can be estimated to be u_d=0,1 % (with coverage factor 1).

According to (4), we can calculate the uncertainty of our reference system (with a coverage factor 1) being

$$u_B = \sqrt{0,37^2 + 0,058^2 + 0,1^2} = \pm 0,39 \%$$

Extension. of the confidence level to respectable 95 % still leaves us a relatively low reference system uncertainty

$$u_B = \pm 0,78 \%$$

4. REFERENCE SYSTEM VERIFICATION

Calculated low uncertainty of the reference system indicates it's capability to became a national standard for low frequency magnetic field, and be used for magnetic field-meters calibration within the legal control of electromagnetic fields in human environment.

To verify the calculated accuracy of the reference field generation, a small coil probe has been dimensioned and carefully manufactured, so that it's inductance is precisely known. The coil was placed at the centre of the reference coil, which was powered by a stabilized source of the sine waveform current. By means of probe voltage, the field value at the centre was measured and compared to the field value determined. from the coil factor. The difference did not exceed 0,45 %, proving the high accuracy of reference field generation.

To test the reference system capabilities in practice, the reading of 5 different field-meters has been tested in the reference field, the same way as it would be done during calibration.

Each of 5 tested meters has a 3D probe, which contains 3 coils, assembled together facing 3 orthogonal space directions. Therefore, each meter is tested in 3 different (orthogonal) positions, marked with x, y, and z.

Meters are marked as M1 to M5, and results of field-meter testing are presented in Table III, at the end of the paper (next page).

In the first colon of the table the referent field values, calculated by means of coil factor, are stated (bold) while other colons contain field-meters readings in three different positions (x, y, and z). The average values, and meter errors are calculated and stated in the table as well.

Meters have been tested in power frequency field of 50 Hz, which is common around the most sources of low frequency magnetic field.

The only potential problem, encountered during this test, were magnetic disturbances coming from environmental fields in the faculty building, which were evident at the low values of the reference field.

Calibration results have been compared to the meters technical specifications, and exhibited errors showed perfect concordance with the specified field-meters accuracy.

3. CONCLUSION

A system for generation of low frequency reference magnetic field has been constructed and tested.

The accurate field calculations, as well as the system practical verification, proved the system ability to generate highly uniform reference magnetic field with high accuracy.

That ability makes this reference system appropriate for realisation of the national magnetic field standard, which could be used for calibration of field-meters used in legal environmental measurements.

To preserve a low calibration uncertainty at the lower reference field values, some problems still have to be resolved. As the most important appears the elimination of magnetic disturbances during calibration in weak reference fields, which can be achieved by construction of an adequate Faraday's cage.

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TABLE III. Results of 5 field-meters calibration

B /µT	Meters	M1	M2	M3	M4	M5
0,9970	x	0,988	0,989	0,970	0,991	0,966
	y	0,966	0,987	0,965	0,987	0,970
	z	0,983	0,984	0,993	0,986	0,970
	av.	0,979	0,987	0,976	0,988	0,969
	Error /%	-1,80	-1,33	-2,40	-1,20	-3,13
4,9998	x	4,991	4,996	4,878	4,965	4,920
	y	4,949	4,951	4,813	4,956	4,880
	z	4,958	4,914	4,878	4,957	4,830
	av.	4,966	4,954	4,856	4,959	4,877
	Error /%	-0,68	-0,92	-2,87	-0,81	-2,46
50,028	x	49,41	49,12	48,52	49,43	49,60
	y	49,35	49,35	47,96	49,62	47,40
	z	49,39	49,19	48,55	49,57	48,10
	av.	49,38	49,22	48,34	49,54	48,37
	Error /%	-1,29	-1,61	-3,37	-0,97	-3,32
100,19	x	100,20	99,52	97,00	99,16	99,00
	y	98,57	99,88	96,48	99,28	95,20
	z	98,50	99,51	97,86	99,26	96,20
	av.	99,09	99,64	97,11	99,23	96,80
	Error /%	-1,10	-0,56	-3,07	-0,96	-3,39
494,05	x	542,0	489,0	482,0	489,4	493,0
	y	520,0	496,0	486,0	491,7	471,0
	z	511,0	485,0	492,0	490,4	477,0
	av.	524,3	490,0	486,7	490,5	480,3
	Error /%	6,13	-0,82	-1,49	-0,72	-2,78

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