TECHNICAL REPORT

ISO/TR 10305-1

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Road vehicles — Calibration of electromagnetic field strength measuring devices —

Part 1:
Devices for measurement of electromagnetic fields at frequencies > 0 Hz

Véhicules routiers — Étalonnage des appareils de mesure de l'intensité d'un champ électromagnétique —

Partie 1: Appareils pour le mesurage des champs électromagnétiques de fréquence supérieure à 0 Hz

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 10305-1 was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 3, *Electrical and electronic equipment*.

This first edition of ISO/TR 10305-1, together with that of ISO/TR 10305-2, cancels and replaces the first edition of ISO/TR 10305, which has been technically revised.

ISO/TR 10305 consists of the following parts, under the general title *Road vehicles — Calibration of electromagnetic field strength measuring devices*:

— *Part 1: Devices for measurement of electromagnetic fields at frequencies > 0 Hz*

— *Part 2: IEEE standard for calibration of electromagnetic field sensors and probes, excluding antennas, from 9 kHz to 40 GHz*

Introduction

The necessity for EMC (electromagnetic compatibility) testing of road vehicles and their components has led to the publication of a number of standardized test procedures. The need, too, for a standardized method for the calibration of field strength measuring devices was seen by the responsible ISO subcommittee. As no such International Standard was at the time available from either ISO or IEC, ISO/TR 10305 was published in 1992, based on the amended 1975 edition of the US National Bureau of Standards (now the National Institute of Standards and Technology, NIST) report, NBSIR 75-804.

That document having been considered incomplete, two new calibration methods were independently developed by DIN, the German Institute for Standardization, and by IEEE, the US Institute of Electrical and Electronics Engineers. It was decided to publish the methods as the two parts of a Technical Report replacing ISO/TR 10305:1992. Part 1 is an English translation of part 26 of DIN VDE 0847 and part 2 is the adoption, unchanged, of IEEE std 1309-1996. Each of the two parts should be considered as independent of the other, no effort having been made to combine them.

The user of either method is kindly requested to report on the experience to ISO/TC 22/SC 3.

In the event of IEC publishing a general calibration procedure as an International Standard, ISO/TR 10305 could be withdrawn, as there is no anticipated need for special calibration methods for use in the automotive industry.

Road vehicles — Calibration of electromagnetic field strength measuring devices —

Part 1: Devices for measurement of electromagnetic fields at frequencies > 0 Hz

1 Scope

This part of ISO/TR 10305 specifies techniques for calibrating field strength measuring devices used in automotive testing for the measurement of electromagnetic fields at frequencies greater than 0 Hz, for both EMC and human protection applications. It has been prepared by German experts using devices including capacitor or coil arrangements, TEM cells and antenna arrangements in absorber-lined chambers. In the automotive field, these field strength measuring devices are used for measurements specified in the various parts of ISO 11451 and ISO 11452.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
field strength measuring device
complete system, consisting of a field probe, data transmission system and display or control device

2.2
field probe
entire transducer unit (i.e. with antennas, detectors, filters, etc.), which converts the field strength into an electrical or optical signal

2.3
field sensor
part of the field probe that receives the field and transfers it for further evaluation

2.4
anisotropy
dependence of the indicated value of a field strength measuring device on the direction of incidence and the polarization of the field, the anisotropy factor being the ratio between the maximum and minimum values of the indicated field strength

2.5
linearity
measure of deviation from a first order polynomial of two variables such as the indication of a field strength measuring device and the field quantity being measured

2.6
calibration field
linearly polarized electrical or magnetic field with a known field strength, or travelling wave field with known energy flow per unit area, having a sufficiently homogeneous volume for the exposition of the field strength measuring device

NOTE The following vectorial field quantities are used:

— electric field strength, E, in volts per metre;

— magnetic field strength, H, in amperes per metre;

— magnetic flux density, B, in tesla;

— power flux density, S, or energy flow per unit area in watts per square metre.

2.7
reference system
orthogonal system of coordinates with one of its axes oriented along the field vector of interest for the particular calibration test

2.8
preferred axis
axis of a field probe determined either by the axis of symmetry (main axis) of the sensor or by the direction of the feed line

NOTE If its position is not obvious, it is determined, marked and documented by the calibration laboratory.

3 Layout and properties of field strength measuring devices

3.1 Layout and functional principles

The field strength measuring devices used for checking measured values against limits for the purpose of EMC or the protection of humans comprise the following:

— field sensor, for example, electrically short dipole (loaded or unloaded), loop antenna, horn antenna, capacitor arrangement;

— transducer for converting the field quantity into a current or voltage, for example, diode, thermocouple, bolometer or opto-modulator;

— data transmission line, for example, resistive cable, fibre optic cable, co-axial cable, wave guide;

— display unit.

Field sensor and transducer are usually combined in the field probe. Some field strength measuring systems allow the field sensor to be either connected to the data transmission line or directly to the display unit. Some designs incorporate both field sensor and display unit in one compact set-up.

The characteristics of field strength measuring devices for protection of humans and for EMC applications are usually broadband and not selective, for example, field strength measuring devices in the telecommunications field. Depending on the field quantities E, H, B or S, different field sensor/transducer combinations are applied.

See Figure 1.

3.2 Properties

3.2.1 General

The influence of all components of the field strength measuring device on the measurement result shall be known and shall be described in the technical documentation, to allow the conditions for calibration to be determined.

3.2.2 Field probes with diode-detectors

This type of field probe uses electrically short dipoles ($< \lambda/4$ of the highest measurable frequency) or small coils, dimensioned and frequency-corrected according to the measuring bandwidth, to which the diodes are connected directly or via frequency correction elements. The diode output is filtered, amplified and displayed as field strength value.

Advantages:

— high sensitivity (best suitable for low field strengths);

— high overload capacity;

— simple technology in probe manufacturing;

— short response time;

— good zero stability.

Disadvantages:

— linearity problems (i.e. small signals result in a voltage proportional to the square of the field strength while large signals are directly proportional to the field strength);

— simultaneous signals or pulsed fields may cause incorrect measuring results;

— results are not necessarily r.m.s. values for distinct types of signals;

— sensitive to light and infrared radiation (photo effect), and temperature changes (diffusion potential), which may result in zero-shifts and changes of sensitivity.

3.2.3 Field probes with thermocouple detectors

These field probes contain thin-film thermocouples which function as field sensors (i.e. electrically short dipoles) and also as absorbers for the RF energy. The DC-current supplied by the thermocouples is proportional to the squared field strength. In the ultra-high frequency range, the power flux density is also measured with ultra-high frequency power meters in combination with horn antennas, the coaxial power meter heads also being based on the thermocouple principle (disc-shaped 50 Ω terminating resistor with vapour deposited temperature detectors).

Advantages:

— large bandwidth;

— measuring signal is proportional to the square of the electric field strength and thus suited for direct measurement of the power flux density in the far field;

— true r.m.s. measurement for random signal types, especially when simultaneous signals or pulsed fields are present;

— relatively immune to ambient temperature changes, as the second connection of the thermocouple is located outside the field and acts as a reference compensating any changes of the ambient temperature.

Disadvantage: very low overload capacity, peak values of pulsed signals need to be carefully monitored.

3.2.4 Field probes with bolometer-detectors

The measurement principle is based on a bolometer element, usually a thermistor, heated by an RF current, its resistance change being evaluated in a bridge. Field probes of this type are exclusively used for power flux density measurements. The thermistor is located in either a wave guide or a coaxial thermistor head connected to, for example, a horn antenna as a field sensor.

Advantage: high overload capacity, since the resulting change of the resistance of the thermistor leads to a mismatch of the measuring head and thus to a limitation of the absorbed power.

Disadvantage: sensitive to changes of the ambient temperature, which may cause a zero-shift of the bridge unless a complicated balancing circuit with an additional thermistor is used.

3.3 Response characteristics

3.3.1 Field probes with isotropic response characteristics

The orthogonal arrangement of three field-sensor/detector-combinations results ideally in a field probe with isotropic response characteristics.

This simplifies the use of the probe, as it does not require adjustment in the field. A disadvantage is that the test engineer may not notice a failure of one or even two sensor elements.

3.3.2 Field probes with directional characteristics

Field probes with only one field-sensor/detector combination require an orientation of the sensor which leads to a maximum reading at the measuring device. Advantageous, however, is the clear recognition of polarization and direction of incidence of the field. This equally applies to combinations of a power meter with power measuring head and a matched horn antenna (in the case of circular polarization, additional correction is necessary) used for power flux density measurements in the far field.

4 General requirements for calibration procedures

Calibrations made in accordance with this part of ISO/TR 10305 shall result in correct field strength measuring results which may be used if requested for documentation in a quality assurance system. For this procedure, only those calibration procedures may be applied where the set field strength can be unambiguously traced back in a suitable way to the national standards. This may be achieved by two different methods: the generation of a calculable field (standard field or standard antenna method) of traceably measured values, or by setting the field strength via a traceably calibrated transfer sensor.

The total uncertainty of the calibration results from the uncertainty of the established field and the contribution of the device under test (DUT). In Clause 5, only the uncertainty of the established field is described.

Since the measurement values indicated on usual field strength measuring devices may be influenced by the chosen set-up and by handling details, the calibration procedure shall simulate the expected applications as closely as possible and shall show whether the requirements for the measuring device can be fulfilled, for example, through

— exposition of sensor or complete equipment,

— determination of the frequency response with frequency step sizes small enough to allow the detection of resonances,

— determination of the anisotropy (of respective sensors) through measurements with at least three different orthogonal field polarizations, one axis being in the preferred axis of the sensor (the rotation should take place around the centre of the field sensor),

— investigation of the linearity,

— investigation of the performance during, respectively, multiple frequency reception and modulation,

— recognition of E-field sensitivity of magnetic field sensors,

— monitoring of the function by means of a 360° rotation of the sensor under the analytical angle of 54° in order to recognize a failure of any sensor element, and

— consideration of the response time.

The cost of calibration may be reduced by suitable calibration intervals and — if possible — simplified calibration procedures, for example, in the case of

— limited frequency or dynamic range,

— known specified field structure,

— special equipment (i.e. “leakage tester”), or

— re-calibration, where the requirements for the determination of anisotropy may be reduced.

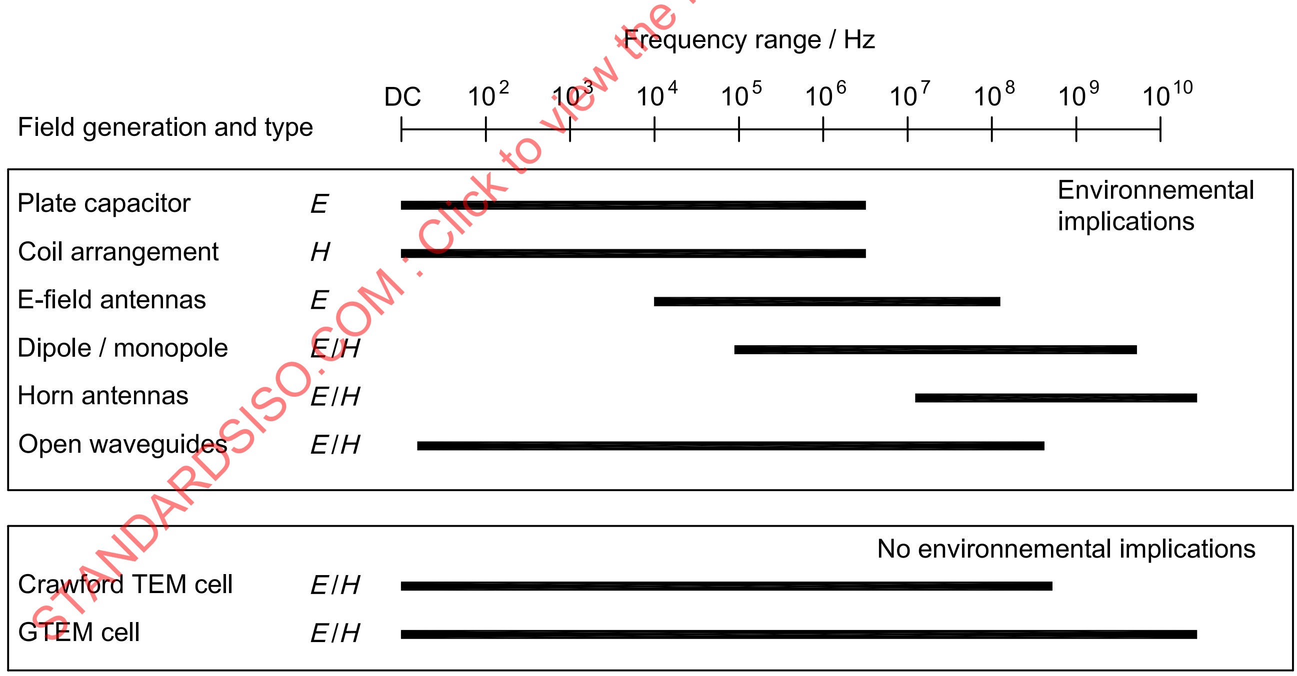


Figure 1 — Typical applications

5 Calibration procedures

5.1 Plate capacitor arrangement

5.1.1 General

For the generation of electrical field strengths for calibration purposes in the frequency range between 0 Hz and about 50 MHz, plate capacitor arrangements may be used, where the shape and distance of the plates are dictated by the requirements of the field homogeneity and the size of the field strength measuring device or field sensor under calibration. If very high field strengths are used in the low frequency range (e.g. 50 Hz), the edges of the plates shall be rounded to avoid corona discharges. The electrodes of the capacitors should be fed symmetrically to ground. A plate capacitor generates an electric field. The accompanying magnetic field may be disregarded.

5.1.2 Applicability and limits of procedure

5.1.2.1 General

Applicability and limits of the calibration procedure depend on the following factors, which are interdependent:

— the size of the capacitor plates vs. their distance;

— the existence of standing waves on the capacitor plates, if their dimensions are close to the wavelength used;

— the interaction of the DUT with the capacitor plates.

These factors determine the upper frequency limit of the procedure and useable test volume with homogeneous field distribution and influence the total uncertainty of the procedure.

5.1.2.2 Field inhomogeneities caused by stray capacitances

If the size of the electrodes of the capacitor in relation to their distance is too small, the field distribution in the capacitor is disturbed by stray capacitances, i.e. the true field strength, E_{actual}, in the region of the DUT is always below the value, E_0, calculated from the voltage at the capacitor, U_0, and the distance of the plates, d:

$$E_0 = \frac{U_0}{d} \tag{1}$$

The relation E_{actual}/E_0 vs. the plate size, a (which is the diameter of a circular plate or the length or width dimension of a rectangular plate), and the plate distance d, is given in 5.1.5.2.3. It results that for a homogeneous field distribution inside the capacitor:

$$\frac{a}{d} > 2 \tag{2}$$

is to be chosen.

5.1.2.3 Restrictions for frequency range caused by standing waves

The relation between the inhomogeneity of the field caused by standing waves on the plates and the maximum permitted plate dimensions is given in 5.1.5.2.1. It is assumed that the voltage along a capacitor plate follows a cosine function from the feeding point. If an inhomogeneity of, for example, 5 % is permitted, the maximum size, a_{max}, of a capacitor plate shall be

$$\cos 2\pi a / \lambda = 0{,}95;\ a_{max} = 0{,}05\lambda \tag{3}$$

At a frequency of 50 MHz, this leads to a_{max} = 0,3 m, i.e. only field probes with sizes below 30 mm may be calibrated.

5.1.2.4 Usable volume

The volume V_p that may be occupied by the DUT is situated in the geometrical centre between the plates, if the capacitor dimensions follow the requirements of 5.1.2.1 and 5.1.2.2.

Its maximum permitted size can be calculated from

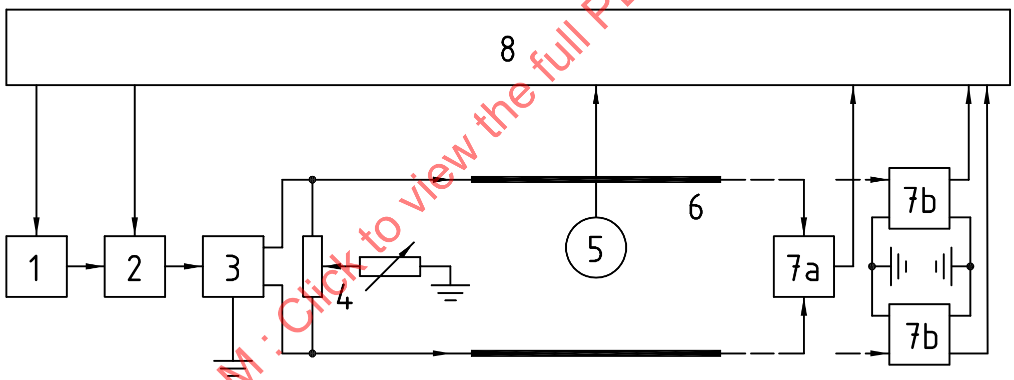
$$V_p = h^3; h \leqslant \frac{d}{5} \tag{4}$$

5.1.2.5 Maximum generated field strength

The maximum field strength which may be generated with a capacitor arrangement is restricted only by the breakdown voltage of air and the material which supports the capacitor plates. It is possible to generate very high electric field strengths with low generator power.

5.1.3 Calibration set-up

Figure 2 shows the basic capacitor arrangement for the calibration of field strength measuring devices.



Key

1 signal generator
2 broadband amplifier
3 balun
4 circuit for changing potentials and impedances of the capacitor plates to ground
5 DUT
6 capacitor plate
7a symmetric voltmeter
7b voltage measurement with voltmeters with input and output symmetrical to ground
8 control unit

Figure 2 — Block diagram of the calibration configuration

The capacitor plates should be arranged vertically and in the centre of the measuring chamber to minimize environmental influences. In the vicinity of the capacitor, field disturbances caused by objects shall be avoided. If these requirements are fulfilled, the circuit (4 in Figure 2) for the change of potential and impedances is redundant. In the RF range, short cables with low inductance shall be used between balun and capacitor plates (band lead instead of a wire, input at the centre of the plate edges). If the symmetric voltage measurement according to Figure 2 is not feasible, because most RF voltmeters have asymmetric input and output terminals, the use of two voltmeters as shown additionally in Figure 2 is necessary; their measured values have to be added. This variant of voltage measurement clearly shows unsymmetries of the calibration set-up by indicating different voltages. If the voltages to be measured exceed the measuring range of the voltmeters, voltage dividers may be used.

5.1.4 Calibration

5.1.4.1 Insertion of the DUT into the capacitor arrangement

The DUT shall be positioned in the centre of the test volume using supporting material with a permittivity, ε_r, approaching 1. The cable to the DUT shall be oriented perpendicularly to the electric field.

5.1.4.2 Measurement of the field strength

The relation between E_{actual} and E_0 may be determined for a given arrangement by a reference measurement, thus allowing the calibration of the field strength via the voltage measurement. Another possibility is the determination of the generated field strength with a transfer sensor.

5.1.5 Uncertainty considerations

5.1.5.1 General

The relative standard deviation s'_E of the field is composed of the following (uncorrelated) portions:

$$s'_E = \sqrt{{s'_U}^2 + {s'_d}^2 + {s'_{\mathrm{M}}}^2} \tag{5}$$

where

s'_U is the relative standard deviation of the voltage measurement;

s'_d is the relative standard deviation of the measurement of the distance of the plates;

s'_{M} is the contribution of averaging the inhomogeneous electric field across the test volume to the relative standard deviation.

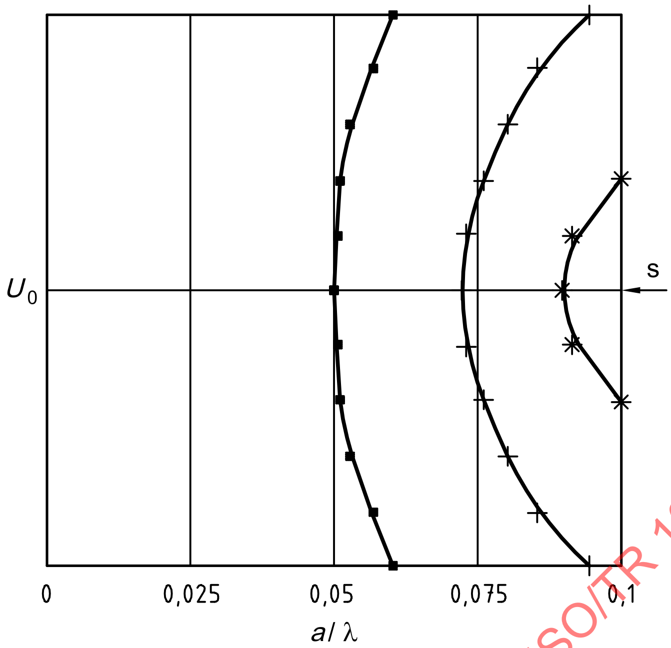
For a 95 % degree of confidence, twice the value of s'_E has to be inserted, representing the uncertainty of the calibration field.

5.1.5.2 Discussion of different contributions

5.1.5.2.1 Voltage measurement

The relative uncertainty of the RF voltmeter (typically 5 % for a 95 % degree of confidence or k = 2, i.e. $s'_U = 2{,}5\ \%$) increases with increasing frequency and is the main portion of the total uncertainty. For higher frequencies, the potential inhomogeneous voltage distribution on the capacitor plates caused by standing waves shall additionally be taken into account, i.e. the voltage measurement becomes dependent on the position.

Figure 3 shows the distribution of the standing waves vs. the relation of plate dimensions and wavelength.

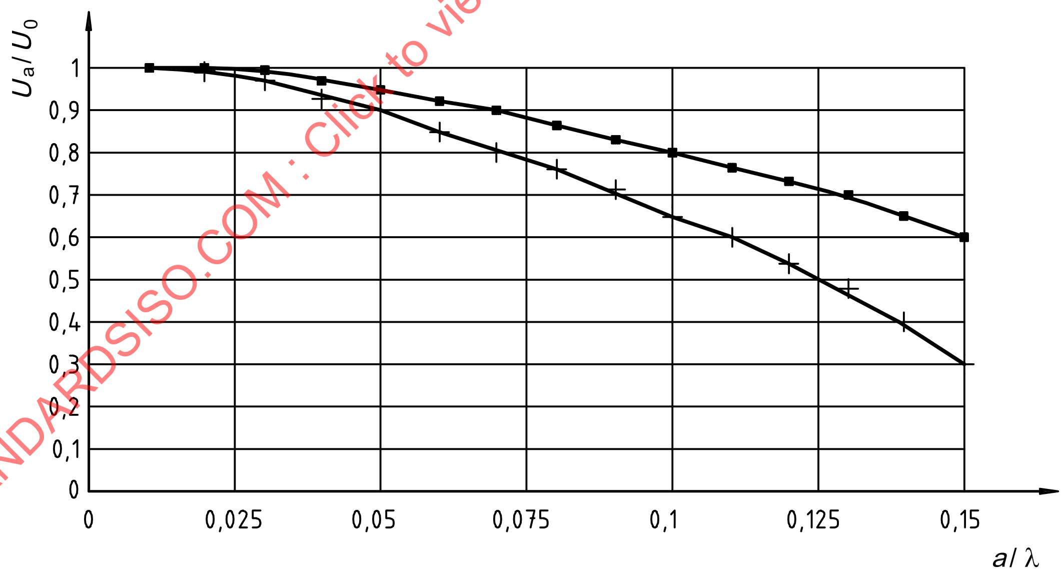


Key

- $U_a = 0{,}9\ U_0$
- $U_a = 0{,}8\ U_0$
- $U_a = 0{,}7\ U_0$

s feeding point

a) Equipotential lines on the capacitor plate with input at the edge of the plate



Key

- calculated
- measured

b) Voltage distribution along the centreline of the plate, calculated with Equation (3) and measured

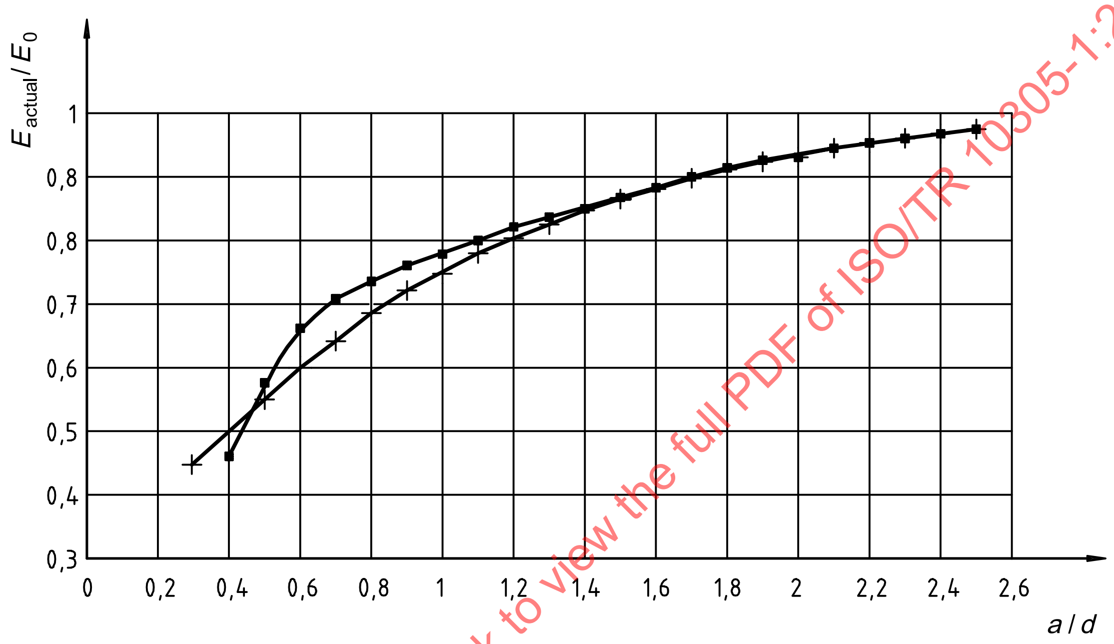
Figure 3 — Distribution of standing waves on the capacitor plates $U_a/U_0=f(a/\lambda)$, where U_a is the actual voltage on the capacitor plate

5.1.5.2.2 Measurement of the plate separation

The separation of the plates in a mechanically rigid apparatus can be determined with high accuracy (e.g. about s'_d = 0,5 %). The contribution of this measurement to the total uncertainty may usually be disregarded.

5.1.5.2.3 Inhomogeneity of the field strength

As the field strength inside the calibration volume of the plate capacitor is not homogeneous, the inserted field measuring device indicates an average value of the field. The resulting uncertainty has to be estimated; typical relative standard deviations s'_H are, for example, s'_H = 2,5 % ... 5 %. The relation of the field strengths E_{actual}/E_0 versus the relation of plate dimension a to plate separation d is shown in Figure 4.



Key

calculated

measured

Figure 4 — E_{actual}/E_0 versus a/d

5.2 Coil arrangements

5.2.1 General

Well defined magnetic fields up to approx. 50 MHz can be produced by means of

a) single-layer cylindrical coils (wound densely or, preferably, with wire gauge spacing),

b) one circular turn, and

c) two circular turns in Helmholtz configuration.

For b) and c), a shielded cable (with an interruption of the shield) may be used. This type is especially suitable for RF and for a direct connection to a generator with an asymmetric output.

The resulting magnetic field strength depends on the number of turns and on the geometric dimensions of the coil and is exactly proportional to the coil current. If the coil layout is sufficiently detailed and the coil current determined with low uncertainty, the strength of the axial magnetic field in the coil centre, suitable for the sensor calibration, can be calculated with the formulas given in Annex A (= standard magnetic field). It is appropriate to express sine-shaped alternating magnetic field strengths and also AC current and AC voltage in r.m.s. values, so that the same formulas are also valid for the frequency 0 Hz.

As these coils are air-core coils, a magnetic field strength of 1 A/m corresponds to a magnetic induction of 1,257 µT because $\mu_r = 1$.

Higher frequencies require coils with lower numbers of turns. Only weaker magnetic fields can be generated, and the strength of the electric field, which is simultaneously generated by the coils, increases in relation to the magnetic field. Since magnetic field sensors are often also sensitive to the electric field, substantial calibration errors can occur.

5.2.2 Applicability and limits

For the above-mentioned coil types, formulas are given in Annex A for the produced axial magnetic field strength, H_0, in the coil centre, and H_x on the coil axis, for the self-inductance, L_E, and the self-capacitance, C_E.

The axial field strength is limited by the maximum RF current, I, which can be fed to the coil. For example, with I = 1 A the field strength, H_0, is

1) in the centre of the single-layer cylindrical coil with 50 cm diameter and 50 cm length with N = 100 turns

$$H_0 = 141\text{A/m} = 178\ \mu\text{T}$$

2) in the centre of a circular turn of ∅50 cm

$$H_0 = 2\text{A/m} = 2{,}51\ \mu\text{T}$$

3) in the centre of a Helmholtz coil of two circular turns of ∅50 cm

$$H_0 = 2{,}86\text{A/m} = 3{,}6\ \mu\text{T}$$

The usable test volume is proportional to the coil size and depends on the accepted inhomogeneity of the magnetic field, i.e. on the accepted decrease of the magnetic field at the boundaries of the test volume (see the curves in Annex A). The sensor to be calibrated must be located in the usable test volume.

The usable frequency range is between 0 Hz and an upper frequency, f_{max}. Depending on the coil type/calibration set-up, the formulas

$$f_{\text{max}} < f_{\text{res}} = \frac{1}{2\pi\sqrt{L_E \cdot C_E}}, \qquad f_{\text{max}} < f_{\text{lim}} = \frac{R_V}{2\pi \cdot L_E} \tag{6}$$

and/or

$$f_{\text{max}} < f_0 = \frac{c}{a \cdot D}$$

apply.

If a set-up has a distinct natural resonance, the natural resonance frequency, f_{res}, of the coil determines the upper frequency, f_{max}, depending on the self-inductance L_E and the self-capacitance C_E.

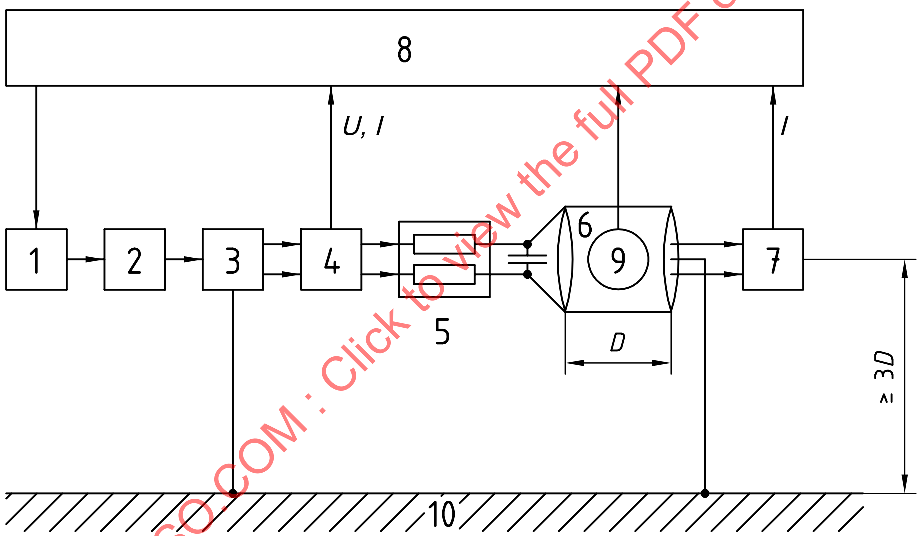
For coils which are operated with series load resistors R_V for current stabilization, the relation $R_V > \omega_{\text{lim}} L_E$ must be maintained and f_{max} is determined by the low-pass cut-off frequency f_{lim}. If $R_V = 3\omega_{\text{max}}L_E$ or $7\omega_{\text{max}}L_E$, i.e. $f_{\text{lim}}/f_{\text{max}} = 3$ and 7, respectively, the current is reduced by 5 % and 1 %, respectively, when f_{max} is approached.

Single turns with a large diameter, D, have a small self-capacitance. In such cases, f_{max} can be determined from the cut-off frequency f_0 of the set-up using the geometric condition that the coil diameter D and the wire-length, $\pi \cdot D$, have to be smaller than the smallest occurring wavelength λ_0 by a factor a.

Considerably higher field strengths with low input power are possible if coils are used which are connected to an external capacitor (parallel capacitor for a generator with high impedance and serial capacitor for a generator with low impedance). This leads to a distinct resonance below the natural resonance, f_{res}, of the coil. The coil systems are then used at this resonance frequency or frequencies near the resonance. The usable frequency range is determined by the Q of the coil system. Additional frequency range may be obtained by changing the value of the external capacitor.

5.2.3 Configuration of calibration set-up

Figure 5 shows the basic configuration of a calibration set-up. The magnetic field is generated by an unscreened single-layer cylindrical coil (diameter D). It can also be generated by one circular turn or two circular turns in a Helmholtz configuration.



Key

1 signal generator
2 broadband amplifier
3 balun
4 RF volt- or ammeter
5 series resistors (identical, symmetric arrangement)
6 field-generating coil
7 RF ammeter
8 control unit
9 field strength meter to be calibrated
10 conductive table-top, connected to ground

Figure 5 — Diagram of coil measuring set-up for calibration of field strength meter or field probe

A balun (3 in Figure 5) must be inserted between the asymmetric output of the amplifier (2) and the earth-symmetric connections of the coil (5) and possibly the RF volt- or ammeter (4). From here on the mechanical set-up and each cable connection shall be electrically symmetric with respect to ground. The geometrically largest component of the set-up is the coil. Its distance from the conductive table-top or from the walls of a shielded room shall be $\geqslant 3D$.

The coil current is alternatively adjusted and measured earth-symmetric or earth-free with (4) or (7). The RF volt- or ammeter (4) contains a differential voltage probe (measurement of the coil current via the voltage drop in series resistors in the cables) or an RF clip-on current probe. For a swept signal generator (1) with a constant output voltage series resistors with $R_V >> \omega_{\text{max}} L_E$ are useful, since this stabilizes the coil current I and makes it independent of the frequency. It may be determined using $I = U/R_V$.

The dimensions of the RF volt- or ammeter (7) are small, as is its capacitance between RF cable and ground and the output cables. In a calibration set-up which is operated close to an intended distinct resonance (using selected additional capacitors in parallel to the coil), the current flow in the coil, must be directly measured using (7).

5.2.4 Calibration procedure

5.2.4.1 Insertion of field strength meter

If possible, the complete field strength meter shall be inserted in the calibration field (see Clause 4), but at least the complete field sensor. The field strength measuring device or the field probe, including transmission lines, shall only negligibly influence the calibration set-up (change of coil inductance and resonance frequency, disturbance of the electric earth symmetry). Measurements and tests using the calibration set-up including the field strength meter under calibration shall demonstrate

— sufficient distance between the upper frequency f_{max} and the resonance frequency f_{res} and the frequency f_{lim}, respectively,

— the earth symmetry, for example by measuring an identical current at either end of the coil or coils, and

— (by varying the routing of the above mentioned transmission lines), that it has been checked and ensured that neither the calibration field feeds coupled disturbances into the leads nor currents in the leads will change the calibration field.

A non-conductive support of the probe shall allow the measuring axis to be aligned parallel and, for monitoring purposes, perpendicular to the vector of the magnetic field strength. It is advisable to check the exact positioning and directional pattern of the probe by tilting it 90° in the “zero direction”.

5.2.4.2 Calibration

Setting the coil current I ensures an axial magnetic field strength in the coil system according to the equations provided in Annex A. After measuring the probe output signals, the correction factors of the field probe can be determined.

5.2.5 Uncertainty considerations

The equations given in A.1 to A.3 for the axial magnetic field strength are exact. The relative standard deviation, s'_H, of the calibration field in the test volume is composed of the following (uncorrelated) portions:

$$s'_H = \sqrt{s'^2_A + s'^2_I + s'^2_{\text{M}}} \tag{7}$$

where

s'_A is the relative standard deviation of the geometrical dimensions of the coil, (production, measurement, mechanical and thermal stability, typically 0,1 % through 1 %, depending on size and construction of the coil);

s'_I is the relative standard deviation of the current measurement (typically 0,1 % through 5 %, depending on frequency and measuring method);

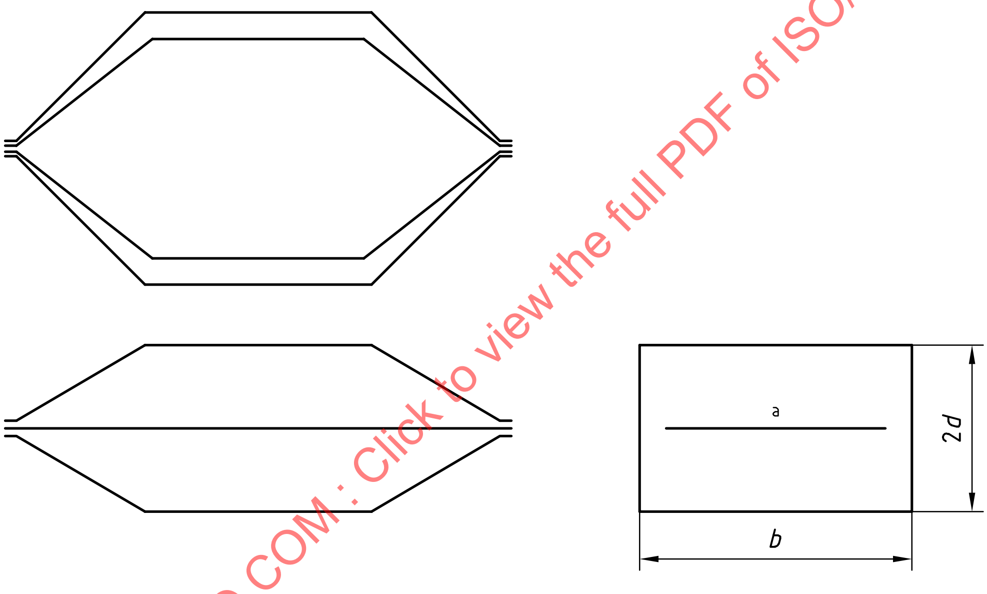
s'_M is the contribution of averaging the inhomogeneous magnetic field across the test volume to the relative standard deviation (typically 1 % to 10 %, depending on the relation of coil dimensions to the size of the test volume).

For a 95 % degree of confidence, twice the value of s'_E has to be inserted, representing the uncertainty of the calibration field.

5.3 TEM cells

5.3.1 General

The TEM cell as shown in Figure 6 represents an expanded coaxial line with a thin inner flat plate conductor (septum) and has a rectangular cross section. Up to a lower cut-off frequency, only a calculable homogeneous transverse electro-magnetic field with vertical electric and horizontal magnetic field component is formed in the cell.



a Septum.

Figure 6 — TEM cell

The geometric dimensions are chosen such that the characteristic impedance Z_L of the cell is 50 Ω along the whole length.

5.3.2 Applicability

5.3.2.1 Mechanical layout and usable volume

The volume V_p with homogeneous field strength distribution usable for the field strength meter calibration is restricted by the geometrical dimensions of the cell. The following estimation is valid:

$$V_p = h^3 \text{ with } h \leqslant \frac{d}{5} \qquad (8)$$

The quality of the impedance matching to the line determines the maximum ripple of the field strength (see 5.3.4) inside the cell. The input reflection factor in accordance with Equation 9 measured at both terminals of the empty cell (see Figure 7) shall fulfil the following conditions:

$$|r| = \sqrt{\frac{P_{\text{rev}}}{P_{\text{fwd}}}} \leqslant 0{,}05 \text{ , i.e. } Z_L = (50 \pm 5)\,\Omega \tag{9}$$

If, for example, a maximum reflection factor $r < 0{,}05$ is accepted, a ripple in the longitudinal direction of the cell as in Equation (14) of approximately 10 % will occur.

The losslessness of the empty TEM cell in the usable frequency range has to be checked by measuring the cell loss a_D in accordance with Equation (10):

$$a_D = \left| 10 \lg \left(\frac{P_{\text{rev}}}{P_{\text{fwd}}} + \frac{P_{\text{out}}}{P_{\text{fwd}}} \right) \right| \leqslant 0{,}5 \text{ dB} \tag{10}$$

Frequency ranges which do not fulfil the conditions of Equations (11) and (12) have to be avoided during calibration.

5.3.2.2 Restrictions to frequency range caused by self-resonances

The usable frequency range for the field strength meter calibration is limited by the occurrence of self-resonances/wave guide modes, which above a cut-off frequency propagate non-attenuated beside the TEM-wave. These lead to an inhomogeneous and incalculable field strength distribution in the cell.

A rough estimation of the lowest cut-off frequency f_c is possible using Equation (11):

$$f_c = \frac{c_0}{2 \cdot b} \tag{11}$$

where c_0 = vacuum light velocity

(Derived from the condition for the critical frequency of the TE_{10} wave of a rectangular wave guide.)

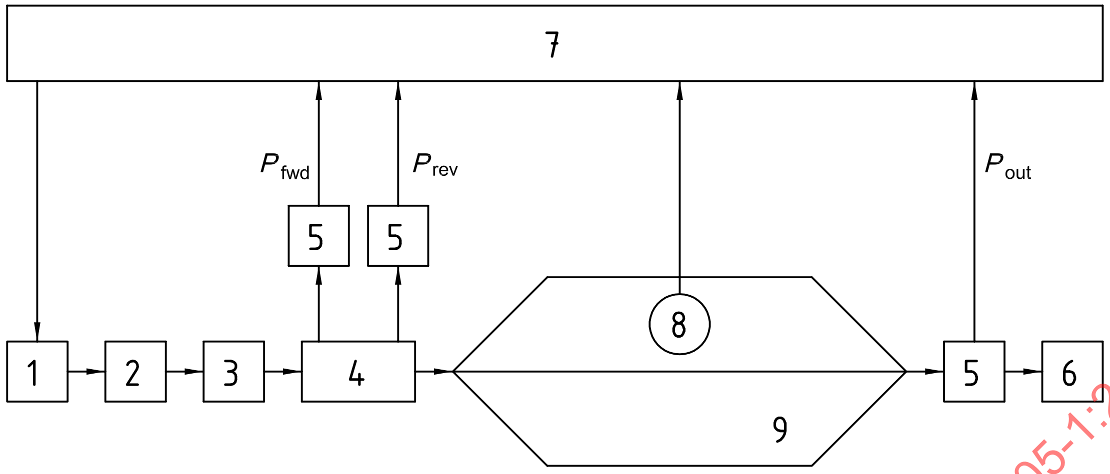
The exact frequencies of the self-resonances can only be determined by a measurement of the frequency response curve of the field strength in the cell at various locations. This should be performed by at least one measurement at a lateral distance of $b/10$ away from the symmetric axis of the cell (b = cell width) and with the field strength meter system that has to be calibrated inserted. A calibration of the necessary field strength sensor with very small dimensions (typically an RF-diode with high impedance leads) is not necessary, since resonances can be detected through large field strength changes. Frequency ranges where resonances occur are to be avoided during calibration.

5.3.2.3 Maximum field strength produced in TEM cell

The maximum producible field strength in the cell is limited only by the breakdown voltage of air or the dielectric material in the pyramid-shaped parts of the TEM cell.

5.3.3 Layout of calibration set-up

Figure 7 shows the basic layout of a measurement set-up. The measurement of the forward power, P_{fwd}, and the reflected power, P_{rev}, at the cell input and the power at the cell output, P_{out}, shall be possible with such accuracy that the conditions of Equation (9) and Equation (10) can also be verified. A low-pass filter (3 in Figure 7) is only required if the attenuation of harmonics at the TEM-cell input is less than 30 dB.



Key

1 signal generator
2 broadband amplifier
3 low-pass filter
4 bi-directional wave guide coupler
5 power meter
6 high power termination 50 Ω
7 control unit
8 field strength meter system to be calibrated
9 TEM cell (Z = 50 Ω)

Figure 7 — Block diagram of TEM cell measuring set-up for calibration of field strength meter system

5.3.4 Calibration procedure

5.3.4.1 Installation of field strength measuring system in TEM cell

If the dimensions of the field strength measuring system do not allow its complete installation in the TEM cell (see 5.3.2.1.), it is usually sufficient to calibrate only the field probe in the TEM cell. The installation can be performed either vertically from the cell's upper side (under the analytical angle 54°) or horizontally from the cell's side wall. The influences of the leads on the field are minimal for an installation from the cell side walls (horizontal position of the leads), since they are orientated perpendicular to the electric field. These leads can short-circuit the TEM-field if their resistance is too low — the effective cell height d between septum and cell wall (see Figure 6) is reduced and the lead impedance influenced — and the result is a simulated increase of the sensitivity of the field sensor.

It has to be ensured that all openings for leads are small compared to the wavelength and that the ground of the field strength measuring system is connected to the TEM-cell housing.

5.3.4.2 Field strength adjustment

With the net power $P_N = P_{fwd} - P_{rev}$ measured at the cell input or the power at the cell output P_{out}, the r.m.s. value of the true vertical electric field component E_{actual} at the location of the sensor head in the TEM cell can be calculated according to Equation (12) if the cell height is known and the line impedance is Z = 50 Ω.

$$E_{actual} = \sqrt{\frac{Z \cdot P_N}{d^2}} \quad \text{or} \quad E_{actual} = \sqrt{\frac{Z \cdot P_{out}}{d^2}} \qquad (12)$$

The magnetic field component can be calculated via the free field impedance Z_0 = 120π Ω from the electric field strength, if needed.

5.3.5 Uncertainty considerations

The expected relative standard deviation, s', of the calibration field strength according to Equation (12) consists of four portions (uncorrelated):

$$s' = \sqrt{\left(\frac{s'_P}{2}\right)^2 + \left(\frac{s'_Z}{2}\right)^2 + s'^2_d + s'^2_W} \tag{13}$$

where

s'_P is the relative standard deviation of the RF power measurement (typically some percent), including mismatch losses of the power meter and the directional coupler and the uncertainty of the coupling factor. The contributions of the directional coupler can be reduced by calibrating coupler and power meter together.

s'_Z is the relative standard deviation of the line impedance (typically < 5 %). If the dimensions of the field sensor surpass d/5 or the impedance of the leads is too low, the impedance of the cell at the position of the sensor is altered. With a pulse reflectometer, the impedance at the position of the sensor may be measured and taken into account [see Equation (12)].

s'_d is the relative standard deviation of the measurement of the distance between septum and upper wall of the cell (typically < 1 %). As this distance can be measured with a relatively high accuracy, these deviations may usually be disregarded.

s'_W is the relative standard deviation resulting from standing waves in the line system (typically < 5 %). Inhomogeneities in the line system create reflections inside the cell and therefore a ripple on the field strength. With known reflection factor r, this relative ripple may be calculated using Equations (14) and (9) as:

$$\Delta E = \frac{E_{max} - E_{min}}{E_0} = 2r \tag{14}$$

where E_0 = field strength in ideal cell, and r<<1.

For a 95 % degree of confidence, twice the value of s'_E has to be inserted, representing the uncertainty of the calibration field.

5.4 GTEM cells

5.4.1 General

The so-called GTEM cell is based on the classic TEM cell and has the shape of a gradually widening coaxial lead with rectangular cross-section, flat internal conductor and integrated load termination (absorber-lined wall and distributed load resistor). A spherical wave propagates inside the cell, which, in the test volume at the end of the cell, is almost homogeneous and linearly polarized. A suitable layout of the feed terminal and the conductor termination prevents the formation of non-TEM waves. In the TEM mode, an electric and magnetic field appears simultaneously according to the free-space wave resistance.

5.4.2 Applicability

5.4.2.1 Frequency range

0 Hz up to several GHz (depending on the design).

5.4.2.2 Available volume and clearance

Large cells offer a clearance of up to 2 m between floor and inner conductor in the test chamber and are therefore suitable for accommodating complete field strength measuring devices for total equipment exposition, permitting also a calibration in different positions (determination of anisotropy). The maximum dimension of the DUT in the direction of the electric field vector should not exceed 1/5 of the septum height.

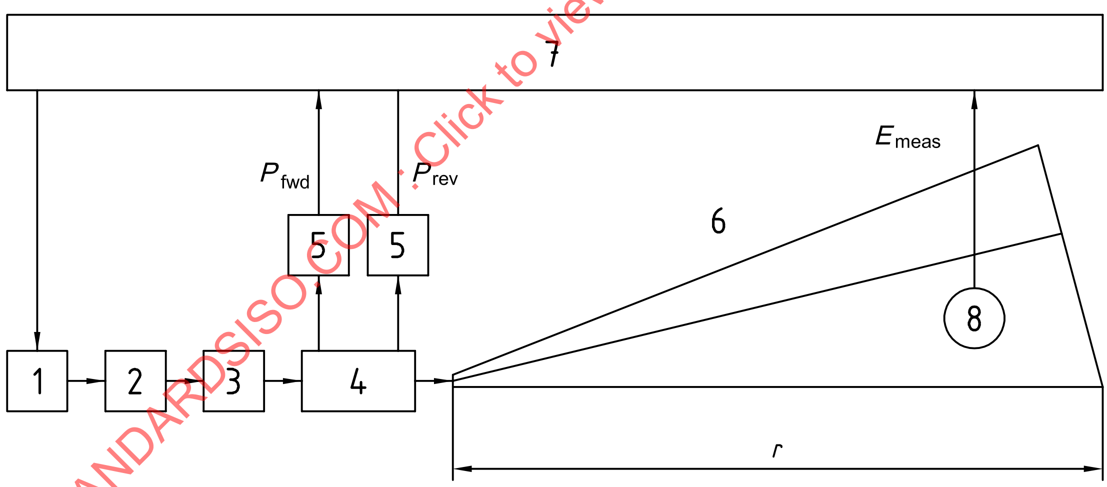
5.4.2.3 Limitations of procedure

Since a spherical wave propagates in the GTEM cell, the field is inhomogeneous. This has to be taken into account if the total uncertainty is calculated.

The frequency range is limited by the (mis)match of the coaxial to the rectangular section, and also by the layout of the conductor termination. In adequately designed cells, the GHz range can be reached. By design the GTEM cell has a frequency range in which the distributed resistance and the absorber wall are simultaneously effective, so that the load impedance is lower than the line impedance. In this range, standing waves and thus additional field inhomogeneity can occur.

The maximum achievable field strength results from the available transmitter power and the dimensions of the cell and is possibly limited by the load capacity of the integrated line termination.

5.4.3 Typical calibration set-up



Key

1 signal generator
2 broadband amplifier
3 low-pass filter
4 bi-directional coupler
5 power meter/RF-voltmeter
6 GTEM cell
7 control unit
8 field strength measuring system to be calibrated

Figure 8 — Circuit diagram of GTEM measuring system for calibrating field strength measuring equipment

5.4.4 Field strength setting

Contrary to the normal TEM cell, the field strength in the GTEM cell cannot simply be calculated from the applied power and the cell geometry. The field strength in the test chamber should therefore be set using a traceably calibrated field sensor. The field sensor is positioned in the empty cell at the location of the DUT and the relationship between applied transmitter power and achieved field strength is registered (reference field measurement). During the calibration, the reference field strength corresponding to the reading on the display, unit can be calculated from the transmitter power.

5.4.5 Calibration procedure

As the electromagnetic field is extended through the whole cell, the DUT must be positioned such that the fixture and the signal leads only cause field distortions, which also appear during the subsequent measurements with the field strength measuring device. The accessories intended for use with the device should therefore be used during calibration, too.

Field strength measuring devices with asymmetric (monopole) sensors shall be placed on the floor of the GTEM cell if they are not specifically intended for measurements in the free field. The displayed value of such equipment is possibly height-dependent.

For field strength measuring devices without integrated data transmission via fibre-optic links, the GTEM cell must provide suitable provisions for remote reading that do not appreciably distort the calibration field.

5.4.6 Uncertainty considerations

It is not yet possible to calculate the field strength in the GTEM cell directly, i.e. it is necessary to adjust it before the installation of the DUT by means of a transfer sensor. The uncertainty of this reference field measurement is substantially influenced by the calibration of the transfer sensor. Additionally, contributions of the (possibly estimated) stability of the sensor and the GTEM cell system and of field inhomogeneities are to be added to the inevitable uncertainty of the transfer sensor. These contributions may be regarded uncorrelated, i.e. the total standard deviation can be calculated as the root of the squared sum of the single standard deviations. For a 95 % degree of confidence, twice this value is to be regarded as the total uncertainty.

5.5 Antennas in absorber-lined shielded enclosures

5.5.1 “Dipole-type” antennas

5.5.1.1 General

“Dipole-type” antennas are half-wave dipoles, broadband dipoles and log-periodic broadband antennas. If they are used for field generation, the field probe to be calibrated should be positioned preferably in the far field of the antenna, so that E-field and H-field are linked via the field wave resistance of the free space.

5.5.1.2 Applicability

For the above antenna types, far field conditions may be supposed at a distance of at least one wave length from the phase centre (distance $d \geqslant \lambda$). For sufficient stability of the field in the calibration volume, the correlation $\Delta E/E = \Delta d/d$ exists. If, for example, the field strength in the calibration volume changes by less than 5 %, $\Delta d/d$ is to be limited to 5 %, too. The radiation pattern of the antenna determines the width and height of the calibration volume. The frequency range of dipole-type antennas for calibrating field probes starts at approximately 80 MHz (100 MHz or more), since at lower frequencies

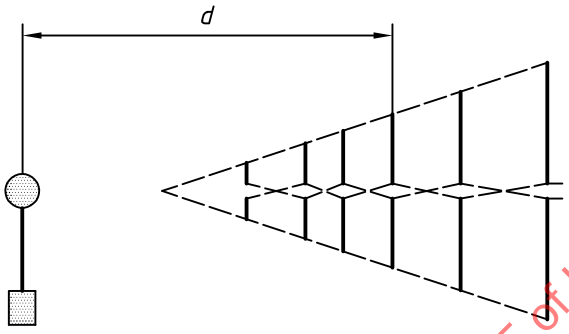
— the dimensions of the antennas and the required distances become too large, and

— the calibration field is distorted by the interaction with chamber resonances of absorber-lined chambers.

The upper frequency limit for dipoles is usually 3 GHz. Above this frequency, other types of radiators are more efficient and there has been sufficient frequency overlap to provide continuous calibration.

5.5.1.3 Typical calibration set-up

The probe is completely installed in the above defined calibration volume. The room used for the field generation shall be equipped with wall and floor absorbers, so that the field strength does not produce standing waves in the vicinity of the DUT. Dipole-type antennas can also be used for measuring the generated field strength. It is important to know, however, that the measuring antenna integrates the field strength across its effective area, i.e. the field strength at the location of the field probe is not indicated if the field in the vicinity of the antenna is not sufficiently homogeneous.



The spacing d is calculated from the respective phase centre of the antenna, thus being frequency dependent. The arrangement with signal generator, power amplifier and control circuit can be used for other calibration set-ups (i.e. for horn antennas — see 5.5.2).

Figure 9 — Typical calibration set-up with log-periodic antenna

5.5.1.4 Field strength adjustment

5.5.1.4.1 Field calculation

The field strength at a position with distance d in the direction of the main beam is calculated as follows:

$$E = \sqrt{\frac{Z_0 \cdot G \cdot P}{4 \cdot \pi \cdot d^2}} = \frac{\sqrt{30 \cdot G \cdot P}}{d} \qquad (15)$$

where

E is the electric field strength, in volts per metre;

Z_0 is the free field impedance;

G is the antenna gain (reference: isotropic radiator) as a numerical value;

P is the consumed power in watts (net power = forward power – reflected power);

d is the distance from the phase centre of the antenna, in metres.

The gain G shall have been measured under free space conditions.

NOTE Gain data for biconical antennas often do not fulfil this condition.

Typical gain values are

— half-wave dipole, lossless: G = 1,64;

— log-periodic antennas (typically): G = 4,5.

5.5.1.4.2 Setting field strength with traceably calibrated field sensor (transfer sensor)

Alternatively, when a transfer sensor is used, the required power is not calculated. The power absorbed by the antenna is adjusted such that the field strength defined for the transfer sensor is measured in the calibration volume. The DUT is then inserted in the calibration volume and the voltage reading is assigned to the existing field strength.

5.5.1.5 Calibration procedure

5.5.1.5.1 Location of field probe to be calibrated

The field probe to be calibrated shall be completely inserted in the calibration field that has sufficient volume to contain the entire probe. Parts of the field probe, such as the display, which are completely de-coupled (e.g. through fibre-optic links) from the probe sensor, may be placed outside the calibration volume.

5.5.1.5.2 Calibration sequence

The net power shall be measured at each calibration frequency such that the calibration field strength can be maintained over the entire frequency range of interest.

5.5.1.6 Uncertainty considerations

5.5.1.6.1 Calculated field

5.5.1.6.1.1 In the case of the calculated field, the calibration uncertainty primarily depends on the uncertainty of the antenna gain data. The uncertainties of the gain and antenna factors usually supplied with antennas are about 1 dB, i.e. they are generally insufficiently exact for the probe calibration. Therefore they have to be individually re-calibrated using an open field calibration method. If log-periodic antennas are used, the positions of the phase centres shall be taken into account even in this gain calibration. With sophisticated calibration methods and with exact attenuation measuring equipment, gain uncertainties in the range 0,3 dB to 0,5 dB can be attained.

5.5.1.6.1.2 A second source of uncertainty is the limitation of the calibration volume (see 5.5.1.2). The size of the calibration volume shall be chosen such that $\Delta E/E$ does not exceed a certain predetermined value.

5.5.1.6.1.3 A third source of uncertainty is the influence of the environment on the calibration volume. While the uncertainty given in 5.5.1.6.1.2 decreases with increasing distance d, the uncertainty caused by the environment increases with increasing d.

5.5.1.6.2 Field calibration with transfer standard

In this case, the uncertainty of the transfer standard and the calibration volume covered by it determine the uncertainty of the calibration. The application of transfer standards is also recommended for checking the calculated field strength.

5.5.2 Horn antennas

5.5.2.1 General

In this procedure, a horn antenna is used as wave-type converter that produces a calibration field with free-field properties. If the region in which the field strength measuring system is placed meets the far field requirement and is free of reflections, the field produced by the horn antenna may be calculated directly.

5.5.2.2 Applicability

The volume, $V_\mathrm{p} = h_3$, usable for the field strength measuring system calibration with homogeneous field strength distribution increases with increasing distance to the transmitting antenna and should comprise at least the volume of the field probe head. The field strength gradient, Δ_grad, in the test volume should be less than 2 %. Independent of other boundary conditions, Equation (16) requires a minimum distance, r_min, to the transmitter antenna of at least 50h.

$$r_\mathrm{min} \geqslant \frac{h}{\Delta_\mathrm{grad}} \qquad (16)$$

It has to be ensured that reflections (e.g. from the floor) do not invalidate the results of the calibration. A reduction may either be achieved by an elevated position of the antenna, a larger elevation angle (see Figure 10) or through absorbers. Furthermore, the test arrangement shall be checked to ensure that the far field conditions exist in the test object volume, i.e. $Z = 120\pi\ \Omega$, and E_0 is proportional to $1/r$. This condition is usually fulfilled if r is greater than $2d^2/\lambda$, where d is the height or diameter of the horn aperture.

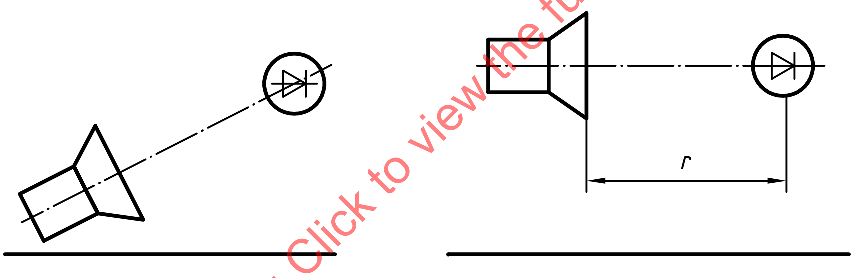


Figure 10 — Reduction of reflections through increased elevation angle or elevated position

Both requirements shall be verified by a measurement of the field strength distribution versus frequency with a reference sensor and for increasing distances r between sensor and phase centre of the horn antenna. Only beyond a distance or frequency or both from where the measured calibration curves, related to the respective distance r, are almost congruent, are reflections unlikely and may far field conditions be assumed.

5.5.2.3 Layout of the calibration set-up

Figure 11 shows the basic arrangement of a measuring set-up. A low-pass filter (3 in Figure 11) is required only if the attenuation of harmonics at the amplifier output is less than 30 dB.

5.5.2.4 Calibration procedure

5.5.2.4.1 Placement of field strength measuring system

The fixture for the system that has to be calibrated in the chamber shall not influence the electromagnetic calibration field, i.e. it shall not comprise conducting materials and, if possible, should be located such that it does not face the transmitter antenna.

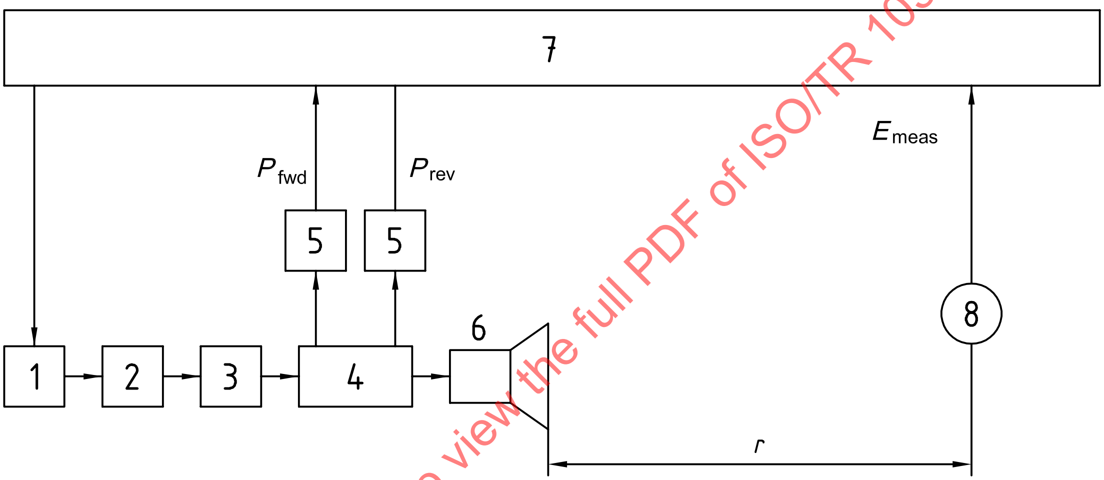
5.5.2.4.2 Field strength setting

With the net transmitter power $P_N = P_{fwd} - P_{rev}$, measured at the antenna base, a known antenna gain G and the distance, r between the field probe head and the phase centre of the horn antenna, the effective value of the true vertical electric field component E_{actual} and the power flux density S_{actual}, respectively, can be calculated at the location of the probe with Equation (15) (standard field method).

$$E_{\text{actual}} = \sqrt{\frac{G \cdot Z_0 \cdot P_N}{4\pi r^2}} \quad \text{or} \quad S_{\text{actual}} = \frac{G \cdot P_N}{4\pi r^2} \tag{17}$$

If necessary, the magnetic field component can be calculated from the electric field strength using the free field impedance $Z_0 = 120\pi\ \Omega$.

Alternatively, the field strength may be set using a transfer sensor.



Key

1 signal generator
2 broadband amplifier
3 low-pass filter
4 bi-directional coupler
5 power meter
6 horn radiator
7 control unit
8 field strength measuring system

Figure 11 — Block diagram of measuring set-up for calibrating field strength measuring equipment in front of horn antenna

5.5.2.5 Uncertainty considerations

The expected relative standard deviation s' of the calibration field strength consists of four portions (uncorrelated):

$$s' = \sqrt{\left(\frac{s'_P}{2}\right)^2 + \left(\frac{s'_G}{2}\right)^2 + {s'_r}^2 + {s'_W}^2} \tag{18}$$

where

s'_P is the relative standard deviation of the RF power measurement (typically some percent), including mismatch losses of the power meter and the directional coupler and the uncertainty of the coupling factor. The contributions of the directional coupler can be reduced by calibrating coupler and power meter together.

s'_G is the relative standard deviation of the gain factor (typically 2 % to 10 %). The gain factor versus frequency of a horn antenna may be determined from its dimensions or by a measurement. For small distances from the transmitting antenna, it shall be taken into account that the antenna gain G is possibly smaller in the near field of an antenna than in the far field. This may be described by a gain correction factor.

s'_r is the relative standard deviation of the measurement of the distance r, this contribution decreases with increasing distance r (transition from the near to the far field). It is mainly determined by the uncertainty Δr of the position of the phase centre of the transmitting antenna:

$$s'_r = \frac{r}{r + \Delta r} \tag{19}$$

s'_W is the relative standard deviation resulting from the ripple on the field strength in the test chamber. This includes disturbances from the environment of the test set-up (e.g. reflections on the floor or at the walls of the chamber), which have to be evaluated case by case. Additionally, the contribution Δ_grad of the gradient of the field strength in the test volume (sensor head dimension h) has to be taken into account.

$$\Delta_\mathrm{grad} = 1 - \frac{r}{r + h} \tag{20}$$

For a 95 % degree of confidence, twice the value of s' has to be inserted, representing the uncertainty of the calibration field.

6 Test and calibration reports

The procedures undertaken by the test laboratories shall be summarized in a report containing all important information in a precise and clear form. Every test report should contain at least the data a) to n) of EN 45001, 5.4.3. Of particular importance is information on the following.

a) General description for each calibration object:

1) technical data, function and clear identification of the DUT;

2) type and content of the calibration task (e.g. according to customer's order);

3) applied calibration procedure;

4) description of the results (e.g. evaluated calibration factors including definition and uncertainty, information on the support points for the calibration curves if necessary, information on anisotropy, linearity, behaviour during modulation).

b) Additionally, in special cases:

1) ambient conditions (temperature, humidity, special conditions if applicable);

2) special test conditions which deviate from normal conditions [e.g. fixture, phantom (“Saltman”) or similar];

3) if the application conditions deviate from the conditions requested by the manufacturer in the handbook of the measuring device (e.g. calibration outside the specified frequency or temperature range), a statement to this effect;

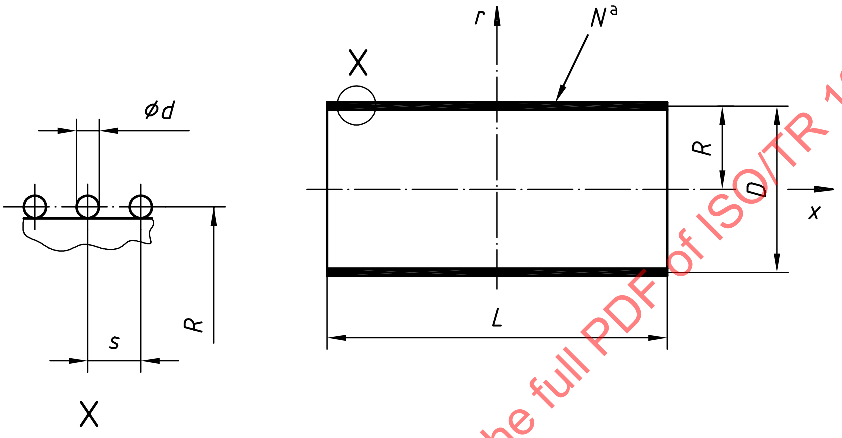
4) observed peculiarities (e.g. zero drift, sensitivity of the measuring device to direct irradiation, E-field influence on magnetic field measuring devices).

Annex A
(informative)

Physical considerations on coils and antennas

A.1 Single-layer cylindrical coils

See Figure A.1.



a Turns.

Figure A.1 — Coil schematics

The axial magnetic field strength, generated by the coil current I in the coil axis, with tight winding (s = d) and distance x to the coil centre is

$$H(x,r=0)=H_x=\frac{IN}{L}\left[\frac{\frac{L}{2}-x}{\sqrt{R^2+\left(\frac{L}{2}-x\right)^2}}+\frac{\frac{L}{2}+x}{\sqrt{R^2+\left(\frac{L}{2}+x\right)^2}}\right] \quad \text{(A.1)}$$

This leads to a magnetic field strength, H_0, in the coil centre (x = 0, r = 0) in relation to the relative coil thickness D/L

$$H(x=0,r=0)=H_0=\frac{IN}{L}\left[\frac{1}{\sqrt{\left(\frac{D}{L}\right)^2+1}}\right] \quad \text{(A.2)}$$

and to the strength of the (homogeneous) magnetic field inside very long coils (where D/L approaches 0):

$$H_\infty=\frac{IN}{L} \quad \text{(A.3)}$$

Equations (A.1) to (A.3) may be used with good approximation for coils wound with a gap between the turns, if $(s/d) < 10$.

The numerical evaluation in Equation A.1 leads to Figures A.2 and A.3 for the estimation of the test volumes. Since the increase of the magnetic field component H_x in direction $\pm r$ to $r \leqslant R/2$ in coils with $L/D \geqslant 0,5$ remains negligible, it is sufficient to take into account the decrease of the axial field strength. Figure A.4 shows that for very short coils with $L/D < 1$, the achievable field strength in the coil centre drops rapidly.

The self-inductance of the densely wound single-layer cylindrical coil may be calculated from

$$L_E = F_1 N^2 D \qquad [\mu H] \tag{A.4}$$

where F_1 is taken from Figure A.5, and D is expressed in metres.

The self-capacitance of the single-layer cylindrical coil does not depend on the coil length and the number of turns, and is

$$C_E \approx F_2 D \qquad [\text{pF}] \tag{A.5}$$

with F_2 taken from Figure A.6 and D expressed in metres. For a dense winding ($s \approx d$), C_E increases rapidly and becomes dependent on the permittivity ε_r of the cable insulation.

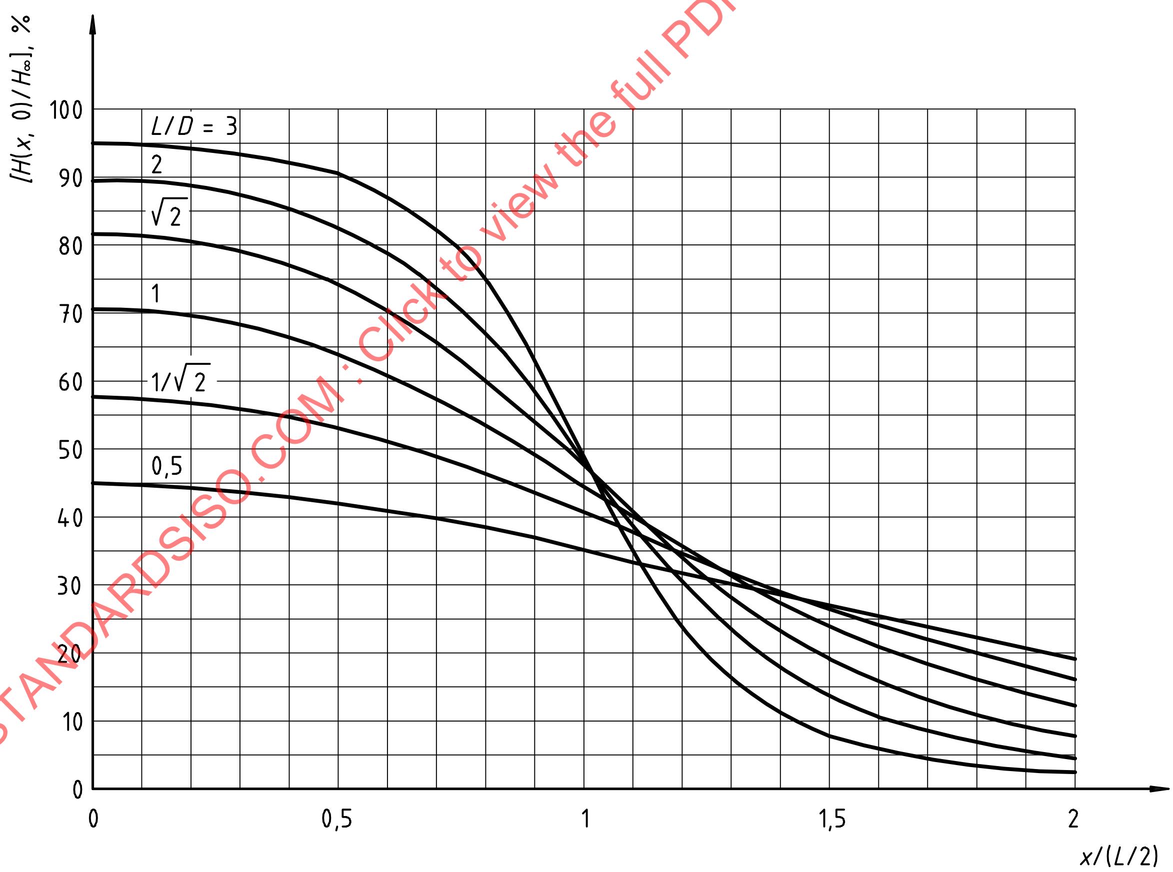


Figure A.2 — Decrease of axial magnetic field strength $H(x,0)$ referred to $H\infty$ with increasing distance x from the coil centre of the cylindrical coil of varying ratio L/D