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Foreword

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This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The magnetic torque, which is created by the interaction between a geomagnetic field and the remnant magnetic moment of the spacecraft, has considerable disturbance on the flight attitude of the spacecraft. The magnetic field of the spacecraft itself will affect a magnetometer scientific payload sensitive to spacecraft-induced magnetic fields. Thus, magnetic tests on Earth-orbiting or interplanetary spacecraft missions with very stringent requirements on magnetic cleanliness are needed in order to ensure that the spacecraft's inherent magnetic properties meet the design goals.

This document provides magnetic test requirements and methods for measuring and evaluating magnetic properties of the spacecraft. The magnetic test methods outlined in this requirements document are effective enough to verify the compliance of magnetic requirements imposed on the spacecraft and to ensure the success of spacecraft flight missions free of magnetic interference and magnetic contamination due to magnetic materials and induced current-generated magnetic fields of the spacecraft.

Space systems — Magnetic testing

1 Scope

This document specifies magnetic test methods including magnetic field test methods, magnetic moment test methods, magnetization and demagnetization test methods and magnetic compensation test methods. This document is applicable to magnetic tests on several levels: spacecraft-level, subsystem-level and unit-level.

This document gives guidelines for conducting magnetic tests both in zero-magnetic field environment provided by magnetic test facilities and in the presence of the geomagnetic field environment.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 14644-1, *Cleanrooms and associated controlled environments — Part 1: Classification of air cleanliness by particle concentration*

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at https://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1
equipment under test
EUT
object under the magnetic test on system, subsystem or unit level generally

3.2
remnant magnetic moment
magnetic moment of the EUT in a zero-magnetic field environment when the EUT is not in a powered on operational mode, that is mostly due to the residual magnetic fields from spacecraft materials

3.3
stray magnetic moment
magnetic moment of the EUT in zero-magnetic field environment when the EUT is in a powered on operational mode

3.4
induced magnetic moment
additional magnetic moment of the EUT generated in an external magnetic field environment when the EUT is not in a powered on operational mode, that is mostly due to soft magnetic materials that easily magnetize in an external magnetic field

3.5
remnant magnetic field
magnetic field produced by the remnant magnetic moment of the EUT as measured at a distance from the magnetic moment location and falls off as the inverse cube of the distance from the magnetic moment location

3.6
stray magnetic field
magnetic field produced by the stray magnetic moment of the EUT in a powered on operational mode

3.7
induced magnetic field
magnetic field produced by the induced magnetic moment of the EUT and mostly due to soft magnetic materials that easily magnetize in an external magnetic field

3.8
zero-magnetic field
magnetic field within a certain volume reduced to very low levels when the geomagnetic field is compensated by a cancelling magnetic field provided by a typical main coil system such as a Helmholtz coil or Braunbeck coil system

3.9
controllable magnetic field
magnitude of magnetic field within a certain volume that is controlled by adjusting electric current of a typical main coil system such as a Helmholtz coil or Braunbeck coil system

3.10
magnetization field
magnetic field used for magnetization tests of the EUT when exposed to a uniform and steady magnetic field for a certain period of time and provided by a magnetization and demagnetization coil system

3.11
demagnetization field
magnetic field used for demagnetization tests of the EUT by exposing them in an alternating sinusoidal magnetic field with a continuously attenuated amplitude and provided by a magnetization and demagnetization coil system

3.12
main coil system
coil system, usually composed of Helmholtz or Braunbeck coils and energized by power supplies, that can provide a zero-magnetic field environment within a given volume of the coil system or that can generate a controllable magnetic field environment by applying the system with calibrated electric current levels

3.13
magnetization and demagnetization coil system
coil system, usually composed of a Helmholtz coil and energized by power supplies, that can provide magnetization and demagnetization fields by applying the system with electric current

3.14
magnetic field stability
variation of the magnetic field at the same location during a certain period

3.15
magnetic field homogeneity
ratio (given in %) of the maximum magnetic field deviation in the volume divided by the magnetic field at the centre of the volume, or the range (given in ± values) of the maximum magnetic field deviation in the volume

3.16
homogeneous volume of magnetic field
spatial volume that satisfies the requirement of magnetic field homogeneity

3.17
soft magnetic material
ferromagnetic material with low field strength (coercivity) that can be magnetized and demagnetized easily

EXAMPLE Invar and Kovar materials.

3.18
hard magnetic material
ferromagnetic material with high field strength (coercivity) that cannot be demagnetized easily

EXAMPLE Permanent magnets.

3.19
compensation magnet
permanent magnet used for magnetic compensation

4 Abbreviated terms

EUT	Equipment Under Test
IMF	Initial Magnetic Field
RMF	Remnant Magnetic Field
SMF	Stray Magnetic Field
IDMF	Induced Magnetic Field
IMDM	Initial Magnetic Dipole Moment
RMDM	Remnant Magnetic Dipole Moment
SMDM	Stray Magnetic Dipole Moment
IDMDM	Induced Magnetic Dipole Moment
MFAM	Magnetic Field After Magnetization
MFAD	Magnetic Field After Demagnetization
MDMAM	Magnetic Dipole Moment After Magnetization
MDMAD	Magnetic Dipole Moment After Demagnetization

5 Requirements

5.1 EUT requirements

When a spacecraft requires the protection of a magnetic sensitive payload such as a magnetometer sensor or plasma search coil and the control of magnetic torque for attitude control, a magnetic cleanliness control plan shall be instituted based on properties and constraints, which are related to mission objectives. This plan should:

a) Prepare magnetic control guidelines, outlining examples on how to control magnetic materials, what materials are acceptable, how to perform tests and to model the overall spacecraft based on magnetic moment results.

b) Establish a magnetic moment budget or allocation list for parts, units, subsystems and spacecraft in the actual magnetic field environment on the orbit, such as the magnetic moment or field of the EUT at low levels of magnetic field and the delta of magnetic moment or field between unpowered and powered mode.

c) Include the steps for reducing magnetic sources. Outline of detailed proven methods for the reduction and cancellation of magnetic fields, elimination of magnetic materials replaced with non-magnetic materials etc.

d) Define magnetic test methods and requirements for parts, units, subsystems and spacecraft.

The steps for reducing magnetic sources include avoiding hard magnetic materials, limiting the use of soft magnetic materials, applying self-compensating configuration of magnetic sources, designing all current carrying and electrical grounding elements to minimize stray magnetic field and stray magnetic moment by self-cancelling methods including solar array backwiring.

5.2 Test requirements

In order to check and control the magnetic properties of the EUT, the magnetic test should be conducted. An example of magnetic test flow is:

a) IMF and IMDM measurement.

b) Magnetization test.

c) MFAM and MDMAM measurement.

d) Demagnetization test.

e) MFAD and MDMAD measurement.

f) Magnetic compensation test.

g) RMF, SMF, RMDM and SMDM measurement after magnetic compensation.

h) IDMF and IDMDM measurement.

References [1]–[5] recommend the magnetic test requirements.

6 Test items

Magnetic test items described in this document refer to magnetic field test, magnetic moment test, magnetization test, demagnetization test and magnetic compensation test.

Magnetic test items are tailored based upon magnetic test requirements for each unique mission or plan. The logic flow of test items is defined according to magnetic requirements imposed for each specific spacecraft.

The magnetic field of the spacecraft will affect precision measurements of magnetic sensitive payload such as magnetometers or plasma wave search coils. Therefore, the spacecraft has requirements on magnetic cleanliness imposed by the sensitivity of the scientific payloads requiring low levels of magnetic fields. According to the requirements, the magnetic field test shall be conducted to predict magnetic cleanliness level of the spacecraft with the goal of meeting the reduced magnetic field levels needed by the sensitive payloads.

The magnetic disturbance torque acting on the spacecraft is equal to the cross-product of the remnant magnetic moment of the spacecraft and the ambient magnetic flux density. If required, the magnetic moment test shall be conducted to predict the flight attitude changes caused by the magnetic disturbance torque of the spacecraft.

Magnetization and demagnetization tests shall be conducted if the spacecraft is easily influenced by the external magnetic fields while on the orbit. Demagnetization tests shall be conducted as a final step in the magnetic testing process well before its launching if the spacecraft may have inadvertently become magnetized after the magnetic tests.

Magnetic compensation tests shall be conducted if the magnetic properties of the spacecraft do not satisfy the overall magnetic cleanliness requirements.

The spacecraft-level magnetic tests for qualification and acceptance are recommended to be conducted after the vibration test. This provides an opportunity to eliminate or reduce any magnetization of the flight hardware caused by the magnetic fields associated with the vibration shaker test facilities, especially for a spacecraft with magnetically sensitive payloads.

References [6]–[7] provide examples of actual implementation of the approach in recent missions requiring magnetic cleanliness.

7 Test room environments

The requirements of test room environments are as follows:

a) Temperature, cleanliness and humidity shall meet customer’s requirements.

b) The air cleanliness in test room shall comply with ISO 14644-1.

8 Magnetic field test methods

8.1 Test purpose

The purpose of magnetic field test is to measure and evaluate magnetic field of the EUT and verify whether it conforms to magnetic field requirements of the EUT.

Magnetic field test methods include RMF, SMF and IDMF measurements of the locations sensitive to magnetic field on the EUT and RMF, SMF and IDMF distribution measurements on a sphere around the EUT.

RMF is mainly generated by magnets, electro-magnets in off-state or residual perm-up (or magnetization) due to hysteresis of soft magnetic materials in the EUT. SMF is generated by electric current flowing within the EUT when in a powered on operational mode. RMF and SMF are independent of the environmental magnetic field. RMF and SMF tests should be conducted in zero-magnetic field.

IDMF is mainly generated by the soft magnetic materials in the EUT. If an external magnetic field is applied to the EUT, the magnetic field measurement result of the EUT may be different in zero-magnetic field. This difference is called IDMF. IDMF disappears when the external field is ceased. IDMF test should be conducted in the controllable magnetic field.

8.2 Test facilities

The test facilities are mainly composed of the main coil system, turntable, fixtures/brackets and magnetic field measuring instruments or test magnetometer sensors. The main coil system shall be able to provide the zero-magnetic field or controllable magnetic field within a given volume where the EUT will be located in the centre of the turntable. The controllable magnetic field also can be provided by the additional coil system. The main coil system access opening shall be large enough to allow the transit of the EUT and its non-magnetic fixture and/or holding brackets into the zero-magnetic field volume. The magnitude, homogeneity and stability of the zero-magnetic field and the controllable magnetic field shall satisfy test requirements.

The turntable shall be rotated from 0° to 360° along the vertical axis, with all angles easily identifiable. The ball bearing capacity of the turntable shall be more than the total weights of the EUT and its fixed bearing. Proof loading of the turntable shall be conducted prior to the test to ensure proper rotation without galling the bearings. The turntable is not required for the magnetic field measurement of locations sensitive to magnetic field on the EUT. The turntable shall be required for the magnetic field distribution measurement on a sphere around the EUT.

The test facilities shall be made of non-magnetic materials. Copper, aluminium, titanium, brass, treated wood and other non-metallic materials are recommended.

The fluxgate magnetometers are recommended for measuring the magnetic field of the EUT. The measurement range and resolution of the magnetometers should be adapted to the required results and accuracy of the magnetic test.

The test facilities and measurement instruments shall be calibrated periodically or in advance of testing and used during its useful-life.

8.3 Procedures for magnetic field test

Two procedures for magnetic field test methods in Annex A are provided as examples: (1) test procedure for locations sensitive to magnetic field on the EUT and (2) test procedure for magnetic field distribution measurement on a sphere around the EUT. The procedures for the magnetic field test shall be selected according to magnetic test requirements.

9 Magnetic moment test methods

9.1 Test purpose

The purposes of magnetic moment tests are to measure and evaluate magnetic moments of the EUT and verify whether it conforms to magnetic moment requirements of the EUT.

The magnetic dipole moment is the major part of the magnetic moment of the EUT, so magnetic moment test methods include RMDM, SMDM and IDMDM measurements of magnetic dipole method, near-field method and multiple magnetic dipole method.

RMDM is generated by magnets, electro-magnets in off-state or residual perm-up (or magnetization) due to hysteresis of soft magnetic materials in the EUT. SMDM is generated by electric current flowing within the EUT. RMDM and SMDM are independent of the environmental magnetic field. RMDM and SMDM tests are conducted in the zero-magnetic field or geomagnetic field.

IDMDM is the induced magnetic dipole moment in soft magnetic materials caused by an external magnetic field. This magnetic moment contribution changes instantaneously with the magnitude and the direction of the external magnetic field. IDMDM test is conducted in the controllable magnetic field.

9.2 Test facilities

The test facilities and measurement instruments for the magnetic moment test in zero-magnetic field shall be the same as those described in 8.2 for the magnetic field test.

The turntable is not required for the magnetic moment measurement of the magnetic dipole method. The turntable shall be required for the magnetic moment measurement with the near-field method and multiple magnetic dipole modelling method.

The main coil system shall be unnecessary for the magnetic moment test in the geomagnetic field. The turntable, fixture/bracket and measurement instruments shall be the same as those described in 8.2.

9.3 Procedures and calculating formulas for magnetic moment test

The procedures and calculating formulas for three magnetic moment test methods (magnetic dipole method, near-field method and multiple magnetic dipole modelling method) shown in Annex B may be used as examples.

The magnetic dipole method is usually used to obtain a rough magnetic moment of the EUT. The near-field method is one of spherical harmonics analysis methods and shall test magnetic dipole moment of the EUT more precisely. The multiple magnetic dipole modelling method is a precise method too. Procedures and calculating formulas for magnetic moment tests shall be selected according to magnetic test requirements.

The magnetic dipole method is commonly used for RMDM, SMDM and IMDM measurements of the EUT. The near-field method and multiple magnetic dipole modelling method are commonly used for RMDM and SMDM measurement of the EUT.

9.4 Magnetic moment test in the geomagnetic field

Magnetic moment test for RMDM and SMDM measurements may be conducted in the geomagnetic field.

Magnetic moment test methods in the geomagnetic field may be used for the EUT where the precision requirement of the measuring result is not high.

The magnetic field induced may be generated by soft magnetic materials of the EUT in the geomagnetic field. When the magnetic moment test is conducted in the geomagnetic field, the magnetic fields induced in the geomagnetic field will have some effect on the measuring results. Magnetic moment test may be conducted in the geomagnetic field for the EUT, under the condition that the EUT contains a sufficiently small amount of soft magnetic material and other magnetic material is hard enough such that only negligible small changes of the remnant magnetization occur in the environmental field. If the magnetic field induced in the geomagnetic field is larger than remnant magnetic field of the EUT, it is better that the measurement method needs to be adapted to eliminate the magnetic field induced in the geomagnetic field from the calculation for the magnetic moment of the EUT.

The magnetic moment test conducted in the geomagnetic field may be influenced by environmental magnetic field perturbations. During magnetic tests, no other magnetic sources are allowed to be close to the fluxgate sensors on the magnetic test site. Environmental magnetic field perturbations may be monitored and eliminated from the calculation for the magnetic moment of the EUT.

10 Magnetization and demagnetization test methods

10.1 Test purpose

The EUT is magnetized for determining the EUT history of magnetic field exposures. The EUT is demagnetized for the removal of the effects of any previous exposures in environmental magnetic field.

The magnetization and demagnetization test is critical for some scientific payloads such as plasma wave search coils, ultra-stable oscillators and magnetometers. Therefore, the need for magnetization and demagnetization test shall be justified.

The test sequence, which is used to inspect the magnetic stability of the EUT, is IMF or IMDM measurements to be the first. Then the EUT is magnetized and MFAM or MDMAM is measured. Finally, the EUT is demagnetized and MFAD or MDMAD is measured. Comparisons between the measuring results after magnetization and demagnetization give susceptible level of magnetic contamination for the EUT.

10.2 Test facilities

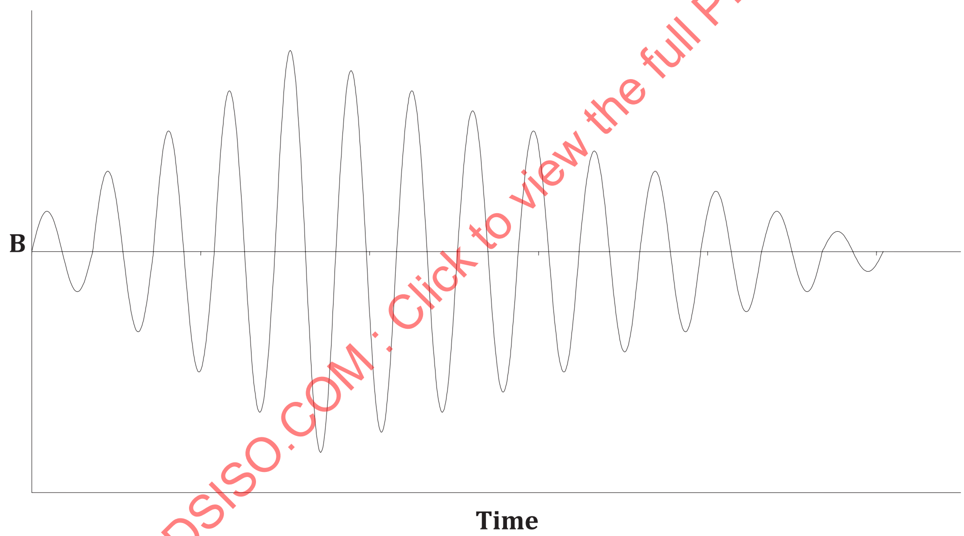
The facilities of magnetization and demagnetization are mainly composed of a main coil system, a magnetization and demagnetization coil system, a turntable, fixtures/brackets and magnetic field measuring instruments. The main coil system, turntable and fixtures/brackets for magnetization and demagnetization tests shall be the same as those described in 8.2 for the magnetic field test.

The main coil system shall be unnecessary if the magnetization and demagnetization coil system is equipped with supplementary geomagnetic field compensation coils for required directions.

The magnetization and demagnetization coil system shall be able to provide a steady (i.e. static) magnetic field for magnetization and an alternating sinusoidal and slowly decaying magnetic field for demagnetization. The coil system access opening shall be sufficiently large that the EUT and its fixture and bracket can be brought into the centre of the coil system. Magnitude and duration of the magnetization field shall be adjustable. Maximum amplitude, frequency and duration of the demagnetization field shall be adjustable and the decrease in amplitude of the demagnetization field shall be set linear or exponential. For example, a wave form of a sinusoidal demagnetization field, whose amplitude is increased or decreased in linearity, is shown in Figure 1. Care shall be taken that the alternating demagnetization field is bias-free and the final absolute field strength value, achieved at the end of demagnetization loop, is much smaller than the geomagnetic field. The magnetization and demagnetization coil system shall be made of non-magnetic materials. Copper, aluminium, brass, titanium and non-metallic materials are recommended.

The Teslameter is recommended to measuring the magnetization field and demagnetization field.

The test facilities and measurement instruments shall be calibrated periodically or in advance of testing and used during its useful-life.



Key

B magnetic field

Figure 1 — Sketch map of the demagnetization waveform

10.3 Procedures for magnetization and demagnetization test

The typical procedures for magnetization and demagnetization test are shown in Annex C.

11 Magnetic compensation test method

11.1 Test purpose

Small compensation magnets may be fixed at optimal locations on the EUT to minimize RMF and RMDM of the EUT. Magnetic compensation with permanent magnets does not work for IDMF and IDMDM. SMF and SMDM need dynamic compensation.

11.2 Procedures for magnetic compensation test

The typical procedures for magnetic compensation test are shown in Annex D.

12 Test report

The test report shall include:

a) purposes and requirements of the test;

b) test room environment report;

c) test facilities, measurement instrumentations and their calibration dates;

d) test items;

e) adoptive test methods and test procedures;

f) names and roles of test participants; and

g) test results.

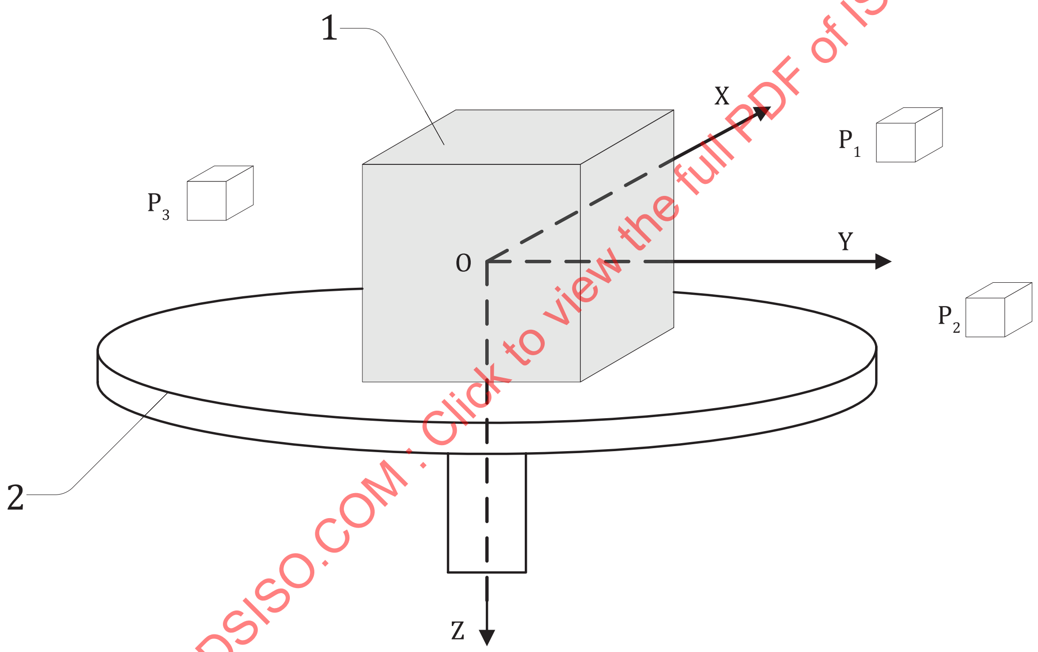
Annex A
(informative)

Procedures for a magnetic field test

A.1 Test procedure for locations sensitive to magnetic field on the EUT

1) A right-handed orthogonal XYZ coordinate system shall be assigned to the EUT's geometric centre in a test volume with zero-magnetic field.

2) The number and positions of magnetic probes (three-axis magnetometer) shall be determined according to test requirements. Magnetic probes shall be installed successively. The probe axes (X, Y and Z) shall be aligned with the XYZ coordinate system. For example, locations of magnetic probes 1, 2 and 3 are shown in Figure A.1.



Key

1	EUT
2	turntable
O	EUT's geometric centre
X, Y, Z	probe axes and EUT's axes
P_1, P_2, P_3	magnetic probes

Figure A.1 — Sketch map of the magnetic field test for locations

3) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable or a platform and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall not be in operation mode or in powered off mode. RMF for locations sensitive to magnetic field on the EUT shall be measured.

4) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable or a platform and the EUT's geometric centre shall be located

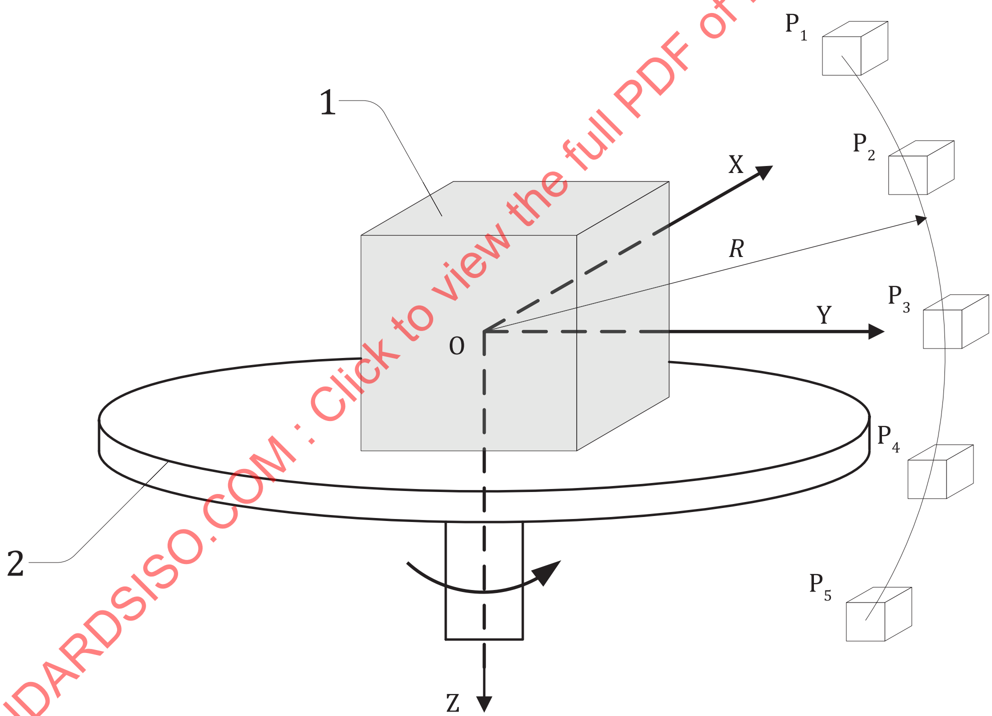
in the centre of the XYZ coordinate system. The EUT shall be in operation mode according to test requirements. SMF for locations sensitive to magnetic field on the EUT shall be measured.

5) The main coil system provides the controllable magnetic field within a given volume at the centre of the coil. The applied magnetic field shall be determined according to the test requirements. The EUT shall be fixed on a turntable or a platform and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall not be in operation mode or in powered off mode. IDMF for locations sensitive to magnetic field on the EUT shall be measured.

A.2 Test procedure for magnetic field distribution measurement on a sphere around the EUT

1) A right-handed orthogonal XYZ coordinate system shall be assigned to the EUT's geometric centre in a test volume with zero-magnetic field.

2) The number and positions of magnetic probes (three-axis magnetometer) shall be determined at a distance *R* on the vertical plane according to test requirements. Magnetic probes shall be installed successively. The probe axes (X, Y and Z) shall be aligned with the XYZ coordinate system. For example, locations of magnetic probes 1, 2, 3, 4 and 5 are shown in Figure A.2.



Key

1	EUT
2	turntable
O	EUT's geometric centre
X, Y, Z	probe axes and EUT's axes
P_1, P_2, P_3, P_4, P_5	magnetic probes
R	spherical radius

Figure A.2 — Sketch map of the test for magnetic field distribution

3) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable and the EUT's geometric centre shall be located in the centre

of the XYZ coordinate system. The EUT shall not be in operation mode or in powered off mode. RMF for magnetic field distribution on a sphere around the EUT shall be measured according to A.2 5).

4) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall be in operation mode according to test requirements. SMF for magnetic field distribution on a sphere around the EUT shall be measured according to A.2 5).

5) The EUT shall be rotated from 0° to 360° along the vertical axis of the EUT and paused with the angular step which is decided by the required spatial resolution of the magnetic field distribution. The magnetic fields shall be measured by magnetometers during the paused period.

Annex B
(informative)

Procedures and calculating formulas for a magnetic moment test

B.1 Magnetic dipole method

B.1.1 Overview

Magnetic dipole method treats the EUT as a magnetic dipole. The magnetic dipole moment of the EUT is calculated by X, Y and Z magnetic field components measured outside the EUT.

The reference distance between the EUT's geometric centre and magnetic probes for magnetic field measurement is usually 3 to 6 times the size of the EUT so that the magnetic field of the EUT is considered "sufficiently close to a dipolar field".

B.1.2 Test procedure and calculating formulas

1) A right-handed orthogonal XYZ coordinate system shall be assigned to the EUT's geometric centre in a test volume with zero-magnetic field.

2) Magnetic probes (one-axis magnetometer) shall be installed at the reference distance *r* for 6 semi-axes of the XYZ coordinate system fixed to the centre of the EUT as shown in Figure B.1. The positive axes of the magnetic probes shall be oriented outward from the EUT's centre and shall be aligned with the XYZ coordinate system successively.

3) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable or a platform and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall not be in operation mode or in powered off mode. The magnetic fields on 6 semi-axes at the reference distances shall be measured according to B.1.2 6) and RMDM of the EUT shall be calculated according to B.1.2 7) and B.1.2 8).

4) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable or a platform and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall be in operation mode according to test requirements. The magnetic fields on 6 semi-axes at the reference distances *r* shall be measured according to B.1.2 6) and SMDM of the EUT shall be calculated according to B.1.2 7) and B.1.2 8).

5) The main coil system provides the controllable magnetic field within a given volume at the centre of the coil. The applied magnetic field shall be determined according to the test requirements. The EUT shall be fixed on a turntable or a platform and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall not be in operation mode or in powered off mode. The magnetic fields on 6 semi-axes at the reference distances *r* shall be measured according to B.1.2 6) and IDMDM of the EUT shall be calculated according to B.1.2 7) and B.1.2 8).

6) The radial magnetic fields at the reference distances *r* for the 6 semi-axes shall be measured.

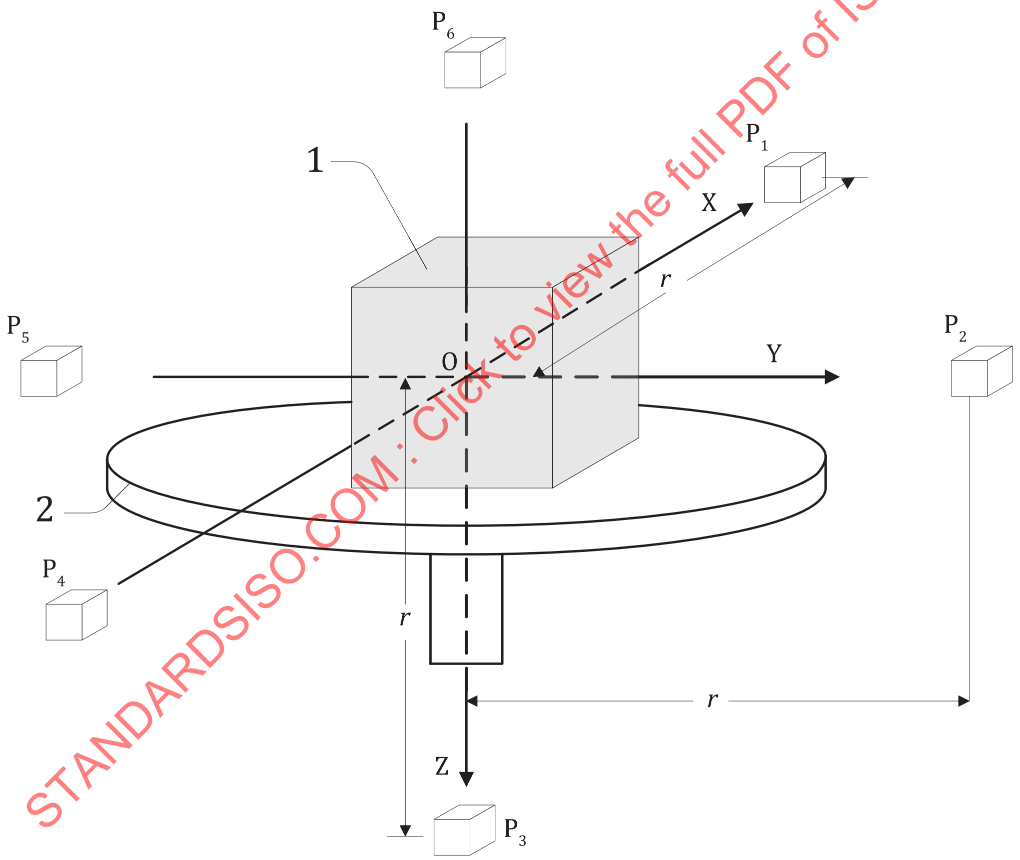
7) Mean magnetic fields for each axis shall be calculated via the following formulas:

$$B_x = \frac{B_{(+X)} - B_{(-X)}}{2}$$
$$B_y = \frac{B_{(+Y)} - B_{(-Y)}}{2} \quad \text{(B.1)}$$
$$B_z = \frac{B_{(+Z)} - B_{(-Z)}}{2}$$

where

$B_{(+X)}$, $B_{(-X)}$, $B_{(+Y)}$, $B_{(-Y)}$, $B_{(+Z)}$, $B_{(-Z)}$ are the magnetic flux density components of the EUT at X, –X, Y, –Y, Z and –Z semi-axis, in nanotesla (nT);

B_x, B_y, B_z are the magnetic flux density components of the EUT at X-axis, Y-axis, and Z-axis, in nanotesla (nT).



Key

1	EUT
2	turntable
O	EUT’s geometric centre
X, Y, Z	probe axes and EUT's axes
P_1, P_2, P_3, P_4, P_5, P_6	magnetic probes
r	distance between the magnetic probe and the geometric centre of the EUT

Figure B.1 — Sketch map of the magnetic dipole method

8) Magnetic dipole moment components shall be calculated via the following formulas:

$$M_x = 5B_x \times r^3 \times 10^{-3}$$
$$M_y = 5B_y \times r^3 \times 10^{-3} \quad (B.2)$$
$$M_z = 5B_z \times r^3 \times 10^{-3}$$

where

r	is the distance between magnetic probe and the geometric centre of the EUT, in metres (m);
M_x, M_y, M_z	are the magnetic moment components of the EUT at X-, Y-, Z-axis, in ampere square metres (A·m^2);
B_x, B_y, B_z	are the magnetic flux density components of the EUT at X-, Y-, Z-axis, in nanotesla (nT).

Reference [8] mentions dipole moment method and calculation formulas.

B.2 Near-field method

B.2.1 Overview

The near-field method adopts a spherical harmonics model. The magnetic moment of the EUT is calculated by magnetic field measured in a limited region close to the EUT.

There are 2 recommended calculation methods for a magnetic moment. The first calculation method is based on the multipole expansion of the EUT's magnetic field. Using the properties of each multipole, the extraneous portions of the magnetic field are eliminated. Thus, the dipole moment of the EUT is calculated. The second calculation method is based that the EUT's magnetic field can approximate superposition of a certain number of multipole fields and a unique solution for the dipole moment exists.

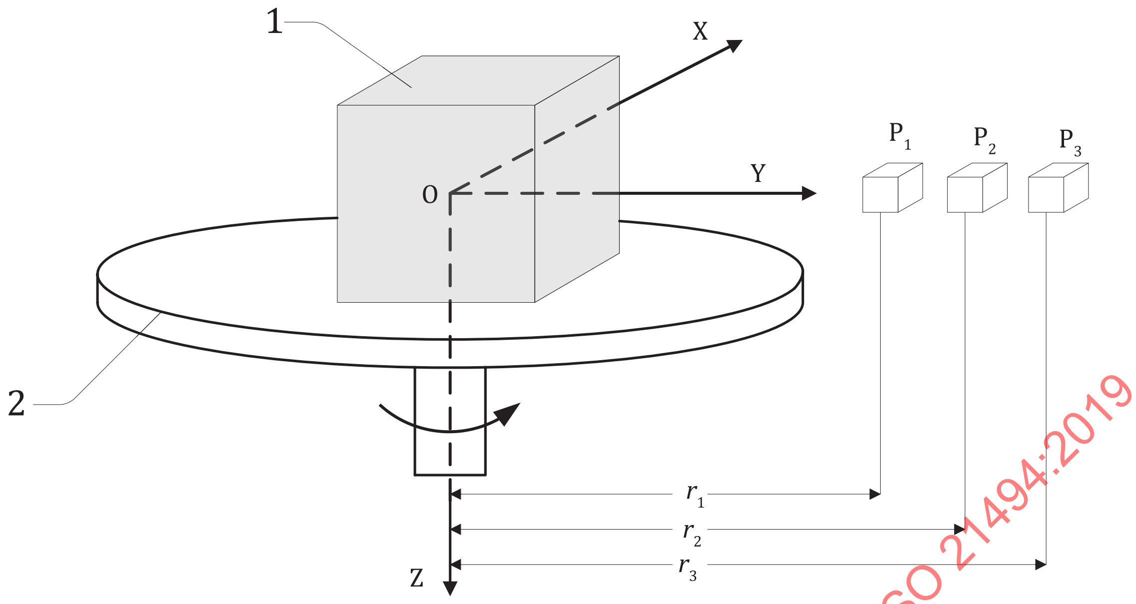
B.2.2 The first calculation method

B.2.2.1 Test procedure

1) A right-handed orthogonal XYZ coordinate system shall be assigned to the EUT's geometric centre in a test volume with zero-magnetic field.

2) The distances from three magnetic probes to the EUT's geometric centre are named r_1, r_2 and r_3 in order. The distances of probes are dependent on the size of the EUT and the resolution of the magnetometers used. For example, r_1 is 1 to 1,5 times the size of the EUT, r_2 is 1,3 to 1,4 times of r_1. The distance from r_2 to r_3 is equal to the distance from r_1 to r_2, so r_3 is the sum of r_2 and the distance from r_1 to r_2.

3) Magnetic probes (three-axis magnetometer) shall be installed at the reference distance r_1, r_2 and r_3 for either X-axis or Y-axis of the XYZ coordinate system fixed to the centre of the EUT. The probe axes (X, Y and Z) shall be aligned with the XYZ coordinate system successively. An example for probes installed at Y-axis is shown in Figure B.2. The following formulas show when probes are installed at Y-axis.



Key

1	EUT
2	turntable
O	EUT's geometric centre
X, Y, Z	probe axes and EUT's axes
P_1, P_2, P_3	magnetic probes
r_1, r_2, r_3	distance between the magnetic probe (P_1, P_2, P_3) and the geometric centre of the EUT

Figure B.2 — Sketch map of the first near-field method

4) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall not be in operation mode or in powered off mode. The magnetic field at distance r_1, r_2 and r_3 shall be measured according to B.2.2.1 6) and RMDM of the EUT shall be calculated according to B.2.2.2.

5) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall be in operation mode according to test requirements. The magnetic field at distance r_1, r_2 and r_3 shall be measured according to B.2.2.1 6) and SMDM of the EUT shall be calculated according to B.2.2.2.

6) The EUT shall be rotated from 0° to 360° along vertical axis of the EUT and paused with the angular step by the required spatial resolution of the magnetic field distribution. The magnetic field at distance r_1, r_2 and r_3 shall be measured during the paused period. For example, 10° is recommended for angular step and the total number of pauses measured during the rotation of the EUT shall be 36.

7) The magnetic moments shall be calculated via the following formulas provided in B.2.2.2.

B.2.2.2 Formulas

B.2.2.2.1 Formulas of the magnetic dipole moment calculation

The calculation formulas are based on the multipole expansion of the EUT's magnetic field, using the properties of each multipole, the extraneous portions of the magnetic field are eliminated, thus allowing the dipole moment to be calculated.

Calculation formulas of the magnetic dipole moment are as follows:

$$M_x = \frac{r_1^{\ 3}}{m} \times 10^{-2} \left[\frac{1}{2} \sum_{j=1}^{m} B_x^{(3)}(j)\cos\phi_j + \sum_{j=1}^{m} B_y^{(3)}(j)\sin\phi_j \right]$$
$$M_y = \frac{r_1^{\ 3}}{m} \times 10^{-2} \left[\frac{1}{2} \sum_{j=1}^{m} B_x^{(3)}(j)\sin\phi_j - \sum_{j=1}^{m} B_y^{(3)}(j)\cos\phi_j \right] \quad \text{(B.3)}$$
$$M_z = -\frac{r_1^{\ 3}}{m} \times 10^{-2} \left[\sum_{j=1}^{m} B_z^{(3)}(j) \right]$$

where

m	is the total number of pauses measured during the rotation of the EUT from 0° to 360°;
j	is the sequential number of pauses measured during the rotation of the EUT from 0° to 360°;
r_1	is the distance from the first magnetic probe to the EUT's geometric centre, in metres (m);
$B_x^{(3)}(j)$, $B_y^{(3)}(j)$, $B_z^{(3)}(j)$	are magnetic flux density components of the EUT after the third time processing on sequential number j, in nanotesla (nT);
ϕ_j	is the rotation angle from sequential number 1 to sequential number j;
M_x, M_y, M_z	are the magnetic moment components of the EUT at X-, Y-, Z-axis, in ampere square metre (A·m^2).

B.2.2.2.2 Formulas of magnetic field data processing

The magnetic field data measured shall be processed for decreasing or eliminating the asymmetry of dipole magnetic field and the influence of multipole magnetic field. Formulas of magnetic field data processing are provided in Formulas (B.4)–(B.6).

1) Formulas for first time processing

$$B_x^{(1)}(n,j) = \frac{1}{2}\left[B_x(n,j) - B_x\left(n, j+\frac{m}{2}\right)\right]$$
$$B_y^{(1)}(n,j) = \frac{1}{2}\left[B_y(n,j) - B_y\left(n, j+\frac{m}{2}\right)\right] \quad \text{(B.4)}$$
$$B_z^{(1)}(n,j) = \frac{1}{2}\left[B_z(n,j) + B_z\left(n, j+\frac{m}{2}\right)\right]$$

where

n is sequential number of magnetic probe, n = 1, 2, 3;

$B_x(n, j)$, $B_y(n, j)$, $B_z(n, j)$ are magnetic flux density components measured by nth probe on sequential number j, in nanotesla (nT);

$B_x^{(1)}(n, j)$, $B_y^{(1)}(n, j)$, $B_z^{(1)}(n, j)$ are magnetic flux density components of the EUT after the first time processing on sequential number j, in nanotesla (nT).

2) Formula for second time processing

$$B_d^{(2)}(e,j)=\frac{(r_e/r_1)^5 B_d^{(1)}(e,j)-B_d^{(1)}(1,j)}{(r_e/r_1)^2-1} \quad (B.5)$$

where

d is the three axis directions, d = x, y and z;

e is sequential number of magnetic probe, e = 2, 3;

r_e is the distance from magnetic probe (e) to the EUT's geometric centre, in metre (m);

$B_d^{(2)}(e, j)$ is the magnetic flux density components after the second time processing on sequential number j, in nanotesla (nT).

3) Formula for third time processing

$$B_d^{(3)}(j)=\frac{(r_3/r_2)^2 B_d^{(2)}(3,j)-B_d^{(2)}(2,j)}{(r_3/r_2)^2-1} \quad (B.6)$$

where $B_d^{(3)}(j)$ is the magnetic flux density components after the third time processing on the sequential number j, in nanotesla (nT).

B.2.3 The second calculation method

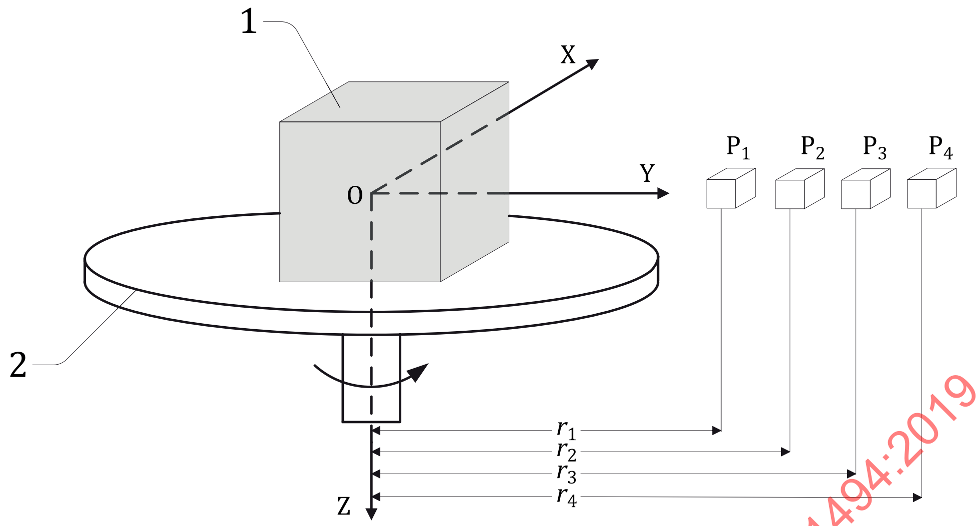
B.2.3.1 Test procedure

1) A right-handed orthogonal XYZ coordinate system shall be assigned to the EUT's geometric centre in a test volume with zero-magnetic field.

2) The number of equations is able to construct for a given number of magnetic probes. In order to obtain a unique solution, the number of unknowns must be less than or equal to the number of equations. An example is assumed that the given number of probes available would be four.

3) The spacing of the probes is neither too close together (r_{max} / r_{min} ≤ 2) nor too far apart (r_{max} / r_{min} ≥ 4). r_1 shall be approximately the diameter of the smallest sphere enclosing the EUT.

4) Magnetic probes (three-axis magnetometer) shall be installed at distance r_1, r_2, r_3 and r_4 for either X-axis or Y-axis of the XYZ coordinate system. The probe axes (X, Y and Z) shall be aligned with the XYZ coordinate system successively. An example for probes installed at Y-axis is shown in Figure B.3. The following formulas show when probes are installed at Y-axis.



Key

1	EUT
2	turntable
O	EUT's geometric centre
X, Y, Z	probe axes and EUT's axes
P_1, P_2, P_3, P_4	magnetic probes
r_1, r_2, r_3, r_4	distance between the magnetic probe (P_1, P_2, P_3, P_4) and the geometric centre of the EUT

Figure B.3 — Sketch map of the second near-field method

5) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall not be in operation mode or in powered off mode. The magnetic field at distance r_1, r_2, r_3 and r_4 shall be measured according to B.2.3.1 7) and RMDM of the EUT shall be calculated according to B.2.3.2.

6) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall be in operation mode according to test requirements. The magnetic field at distance r_1, r_2, r_3 and r_4 shall be measured according to B.2.3.1 7) and SMDM of the EUT shall be calculated according to B.2.3.2.

7) The EUT shall be rotated from 0° to 360° along the vertical axis of the EUT, as well as paused with the angular step by the required spatial resolution of the magnetic field distribution. The magnetic field at distance r_1, r_2, r_3 and r_4 shall be measured during the paused period. For example, 10° is recommended for angular step and the total number of pauses shall be 36, which is measured during the rotation of the EUT.

8) The magnetic moments shall be calculated via the following formulas provided in B.2.3.2.

B.2.3.2 Formulas

B.2.3.2.1 Formulas of the magnetic moment calculation

Calculation formulas of the magnetic moment are as follows:

$$
\begin{aligned}
A_1(i,1,0) &= 10^2 \sum_{k=1}^{\infty} \left(-\frac{1}{2}\right)^{k-1} \frac{2k(2k-1)!!}{(k-1)!} \frac{1}{r_i^{2k+1}} M_{\text{x-}2k-1,1} \\
A_1(i,2,0) &= -10^2 \sum_{k=1}^{\infty} \left(-\frac{1}{2}\right)^{k-1} \frac{(2k-1)!!}{(k-1)!} \frac{1}{r_i^{2k+1}} M_{\text{y-}2k-1,1} \\
A_2(i,1,0) &= -10^2 \sum_{k=1}^{\infty} \left(-\frac{1}{2}\right)^{k-1} \frac{2k(2k-1)!!}{(k-1)!} \frac{1}{r_i^{2k+1}} M_{\text{y-}2k-1,1} \\
A_2(i,2,0) &= 10^2 \sum_{k=1}^{\infty} \left(-\frac{1}{2}\right)^{k-1} \frac{(2k-1)!!}{(k-1)!} \frac{1}{r_i^{2k+1}} M_{\text{x-}2k-1,1} \\
A_0(i,3,0) &= -10^2 \sum_{k=1}^{\infty} \left(-\frac{1}{2}\right)^{k-1} \frac{(2k-1)!!}{(k-1)!} \frac{1}{r_i^{2k+1}} M_{\text{z-}2k-1,0}
\end{aligned}
\qquad \text{(B.7)}
$$

where

k	is the multipole coefficient and equal to the number of probes. When $k = 1$, $M_{\text{x-}1,1}$ is dipole moment. When $k = 2$, $M_{\text{x-}3,1}$ is the quadrupole moment;
i	is the sequential number of probes;
$A_1(i,1,0)$, $A_2(i,1,0)$	are the fundamental cosine amplitudes of the components $B_x(r_i, j, 0)$;
$A_1(i,2,0)$, $A_2(i,2,0)$	are the fundamental sine amplitudes of the components $B_y(r_i, j, 0)$;
$A_0(i,3,0)$	is the dc amplitude of the components $B_z(r_i, j, 0)$;
r_i	is the distance from magnetic probe i to the EUT's geometric centre, in metres (m);
$M_{\text{x-}2k-1,1}$, $M_{\text{y-}2k-1,1}$, $M_{\text{z-}2k-1,0}$	are components of dipole moment and multipole moment, in ampere·metre^{2k} (A·m^{2k}).

B.2.3.2.2 Formulas of amplitudes calculation of magnetic field components

Calculation formulas of magnetic field components' amplitudes are as follows:

$$A_1(i,1,0)=\frac{2}{m}\sum_{j=1}^{m}B_x(r_i,j,0)\cos\left(\frac{2\pi j}{m}\right)$$
$$A_1(i,2,0)=\frac{2}{m}\sum_{j=1}^{m}B_y(r_i,j,0)\cos\left(\frac{2\pi j}{m}\right)$$
$$A_2(i,1,0)=\frac{2}{m}\sum_{j=1}^{m}B_x(r_i,j,0)\sin\left(\frac{2\pi j}{m}\right) \quad \text{(B.8)}$$
$$A_2(i,2,0)=\frac{2}{m}\sum_{j=1}^{m}B_y(r_i,j,0)\sin\left(\frac{2\pi j}{m}\right)$$
$$A_0(i,3,0)=\frac{1}{m}\sum_{j=1}^{m}B_z(r_i,j,0)$$

where $B_x(r_i,j,0)$, $B_y(r_i,j,0)$, $B_z(r_i,j,0)$ are magnetic flux density components measured by the ith probe on the sequential number j, in nanotesla (nT).

References [9] and [10] recommend the second calculation method.

B.3 Multiple magnetic dipole modelling method

B.3.1 Overview

The multiple magnetic dipole modelling method is based on the postulate that any magnetic field configuration can be modelled by any number of individual dipoles. The so-called Multiple Dipole Model is based on near-field measurements and is obtained by optimizing the individual dipoles in such a way that the difference between the calculated and the measured fields is minimal. This approach can be formulated as a classical model parameter identification in the sense of least square fit.

B.3.2 Test procedure

1) A right-handed orthogonal XYZ coordinate system shall be assigned to the EUT's geometric centre in a test volume with zero-magnetic field.

2) The number and position of magnetic probes (three-axis magnetometers are needed) shall be determined at a distance on the vertical plane according to test requirements. The number of three-axes magnetic probes is usually 3 to 4. The reference distance between the EUT's geometric centre and probes for magnetic field measurement is usually 1 to 1,5 times of the size of the EUT. Magnetic probes shall be installed successively. The example for locations of 3 probes is shown in Figure B.4.

3) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall not be in an operation mode or in a powered off mode. The magnetic fields shall be measured according to B.3.2 5) and RMDM of the EUT shall be calculated according to B.3.3.

4) The main coil system provides zero-magnetic field within a given volume at the centre of the coil. The EUT shall be fixed on a turntable and the EUT's geometric centre shall be located in the centre of the XYZ coordinate system. The EUT shall be in operation mode according to test requirements. The magnetic fields shall be measured according to B.3.2 5) and SMDM of the EUT shall be calculated according to B.3.3.

