

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Magnetic materials –

Part 17: Methods of measurement of the magnetostriction characteristics of grain-oriented electrical steel strip and sheet by means of a single sheet tester and an optical sensor

Matériaux magnétiques –

Partie 17: Méthodes de mesure des caractéristiques de magnétostriction des bandes et tôles magnétiques en acier à grains orientés au moyen d'un essai sur tôle unique et d'un capteur optique



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

MAGNETIC MATERIALS –

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The text of this International Standard is based on the following documents:

Draft	Report on voting
68/685/CDV	68/692/RVC

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement to Part 1.

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A list of all parts in the IEC 60404 series, published under the general title *Magnetic materials*, can be found on the IEC website.

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- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

This document provides standard methods to measure the magnetostriction characteristics of grain-oriented electrical steel strip and sheet under an applied AC magnetic field at 50 Hz or 60 Hz. The technical details are specified after intense considerations among magnetostriction experts, so that a satisfactory reproducibility of the measurement can be expected. The measurement requires detections of tiny vibrations of the test specimen at a resolution of 0,01 μm or better. In order to meet this challenging condition, not only the magnetic aspects, but also mechanical aspects of the test apparatus, e.g. the influence of friction, Maxwell forces, resonance and external vibrations, had to be specified.

The methods to determine magnetostriction characteristics of the butterfly loop, the peak-to-peak and zero-to-peak values of magnetostriction strain are specified in this document. Subsidiary characteristics of the velocity levels and the acceleration levels are described in Annex E.

The technical report IEC TR 62581:2010 [1]¹ reviewed the methods of measurement of the magnetostriction characteristics of grain-oriented electrical steel by means of a single sheet tester. Various methods have been used for the measurement of the change in length of the various test specimens. However, for methods using sensors in contact with the test specimen, it is difficult to avoid measurement offsets associated with the contact methods. Moreover, the methods require special skills to be used in order to carry out the measurements. Therefore, this document provides methods using an optical sensor, namely a laser Doppler vibrometer, which fulfils the requirements of non-contact, high resolution and high reproducibility of measurements.

It is well known that mechanical stress in grain-oriented electrical steel has a strong influence on magnetostriction [1]. Grain-oriented electrical steel has a particular behaviour with regards to its sensitivity to compressive stress along the rolling direction compared to other kinds of electrical steels. It depends on the degree of grain-orientation of the material and the level of tensile stress in the material applied by surface coatings. Methods of measurement under an externally applied compressive stress are described in Annex B.

International round robin comparisons of the magnetostriction measurements have been carried out repeatedly by reducing the range of methods [2], [3], [4]. The reproducibility of the measurement was characterized by a relative standard deviation of more than 20 % when various methods were allowed. It became less than 2 % when test apparatuses following the principles described in this document were used for the assessment of grain-oriented electrical steel sheets cut along the rolling direction under the condition of a peak magnetic polarization of 1,7 T and a magnetizing frequency of 50 Hz.

¹ Numbers in square bracket refer to the Bibliography.

MAGNETIC MATERIALS –

Part 17: Methods of measurement of the magnetostriction characteristics of grain-oriented electrical steel strip and sheet by means of a single sheet tester and an optical sensor

1 Scope

This part of IEC 60404 is applicable to grain-oriented electrical steel strip and sheet specified in IEC 60404-8-7 for the measurement of magnetostriction characteristics under an applied AC magnetic field at 50 Hz or 60 Hz.

This document defines the general principles and technical details of the measurement of magnetostriction characteristics of grain-oriented electrical steel strip and sheet by means of a single sheet tester and an optical sensor.

NOTE 1 The accelerometer method [5] is also an established method for the measurement of magnetostriction. However, it is more suited to the measurement of magnetostriction under an externally applied tensile or compressive stress, not zero stress, because it places a weight on the test specimen to prevent a deformation of the test specimen. Since this document includes the measurement at zero stress, the optical sensor method is provided as the optimum method.

This document is applicable to the measurement of:

- the butterfly loop;
- the peak-to-peak value λ_{p-p} ;
- the zero-to-peak value λ_{0-p} .

The magnetostriction characteristics are determined for a sinusoidal induced secondary voltage, for a specified peak value of the magnetic polarization and at a specified magnetizing frequency.

NOTE 2 Throughout this document the term “magnetic polarization” is used as described in IEC 60050-121:1998, 121-11-54. In some standards of the IEC 60404 series, the term “magnetic flux density” is used.

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.

IEC 60050-103, *International Electrotechnical Vocabulary – Part 103: Mathematics – Functions* (available at www.electropedia.org)

IEC 60050-121, *International Electrotechnical Vocabulary – Part 121: Electromagnetism* (available at www.electropedia.org)

IEC 60050-221, *International Electrotechnical Vocabulary – Chapter 221: Magnetic materials and components* (available at www.electropedia.org)

IEC 60050-801, *International Electrotechnical Vocabulary – Chapter 801: Acoustics and electroacoustics* (available at www.electropedia.org)

IEC 60404-8-7, *Magnetic materials – Part 8-7: Specifications for individual materials – Cold-rolled grain-oriented electrical steel strip and sheet delivered in the fully-processed state*

IEC 61672-1:2013, *Electroacoustics – Sound level meters – Part 1: Specifications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-103, IEC 60050-121, IEC 60050-221, IEC 60050-801, IEC 61672-1 and the following apply.

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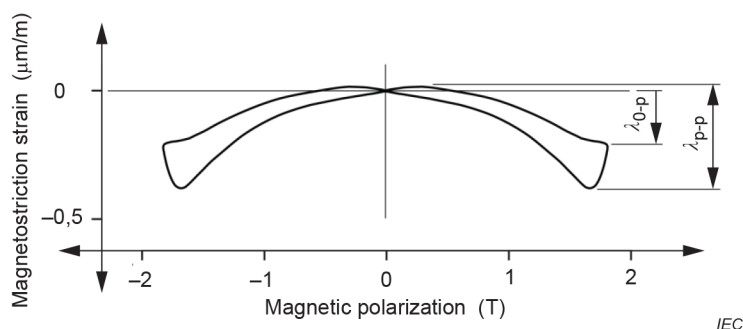
3.1

butterfly loop

butterfly curve

hysteresis loop of magnetostriction strain versus magnetic polarization along the direction of applied AC magnetic field for a period of magnetization, as illustrated in Figure 1

EXAMPLE



Key

- λ_{p-p} peak-to-peak value
 λ_{0-p} zero-to-peak value

Figure 1 – Illustrations of butterfly loop, peak-to-peak value and zero-to-peak value

3.2

λ_{p-p}

peak-to-peak value

peak-to-peak amplitude of magnetostriction strain along the direction of applied AC magnetic field, taking an absolute value, expressed in $\mu\text{m/m}$

Note 1 to entry: The peak-to-peak value can be read from the butterfly loop as shown in Figure 1.

3.3

λ_{0-p}

zero-to-peak value

difference in magnetostriction strain along the direction of applied AC magnetic field between the values at the prescribed peak magnetic polarization and at the zero value of the magnetic polarization, taking a positive or negative value, expressed in $\mu\text{m/m}$

Note 1 to entry: The zero-to-peak value can be read from the butterfly loop as shown in Figure 1.

3.4

L_v

velocity level

indicator of magnetostriction velocity comprising all harmonic components of magnetostriction strain of interest, expressed in dB

Note 1 to entry: The frequency weighting filter "A" defined in IEC 61672-1:2013 can be applied to the velocity level resulting as A-weighted velocity level, L_{vA} , expressed in dB(A).

3.5

L_a

acceleration level

indicator of magnetostriction acceleration comprising all harmonic components of magnetostriction strain of interest, expressed in dB

Note 1 to entry: The frequency weighting filter "A" defined in IEC 61672-1:2013 can be applied to the acceleration level resulting as A-weighted acceleration level, L_{aA} , expressed in dB(A).

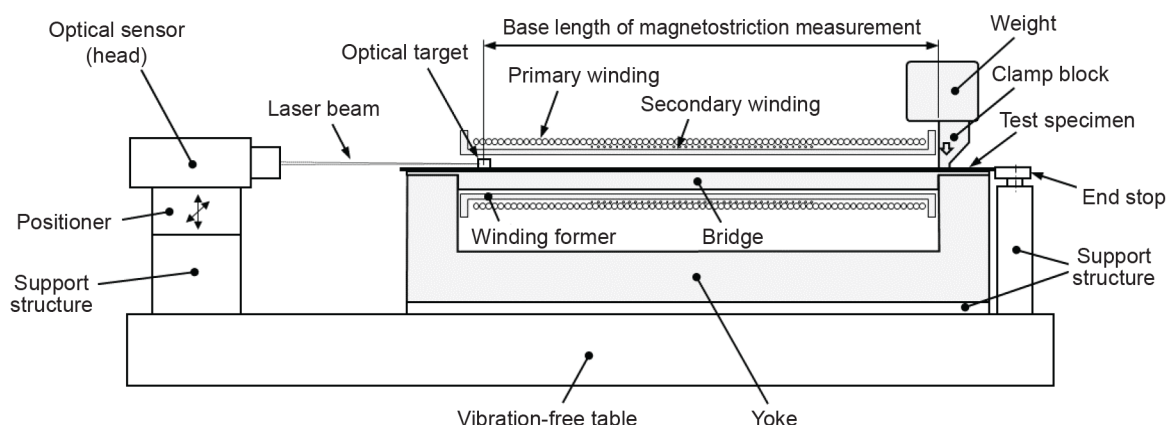
4 General principles

4.1 Principle of the method

A length change of a test specimen for a base length under an AC magnetic field is measured by means of a single sheet tester and an optical sensor. Magnetostriction characteristics of the material are determined from the length change of the base length of the test specimen for prescribed peak values of the magnetic polarization and at a specified magnetizing frequency.

A schematic diagram of a test apparatus is illustrated in Figure 2. The test apparatus consisting of windings, a winding former, a bridge, a yoke, a clamp block, a weight, an end stop, an optical sensor and auxiliary support structures shall be fixed to a vibration-free table. The test apparatus may be assembled on a rigid base plate which is non-magnetic and fixed to the vibration-free table.

NOTE 1 Methods of measurement under an externally applied compressive stress are described in Annex B.



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Figure 2 – Schematic diagram of a test apparatus (cross-sectional)

The test specimen shall be placed on the bridge inside the following two windings wound on the winding former (see 4.3.3):

- an exterior primary winding (magnetizing winding);
- an interior secondary winding (induced voltage winding).

A flux closure shall be made by the yoke placed under the test specimen. The two pole faces shall be in a horizontal plane. The cross-section of the yoke shall be sufficiently large compared to that of the test specimen. Several types of yoke may be used (see 4.3.2).

The winding former shall be placed symmetrically between the two pole faces so that the magnetic field is symmetrically distributed within the winding former. The length of the winding former shall be as long as possible.

The bridge between the two pole faces shall be placed inside the winding former without touching the winding former. The bridge shall be sufficiently rigid to keep the test specimen on it flat, and the surface on which the test specimen is placed shall be flat and smooth with a low friction film adhered to the surface (see 4.3.4).

Both end parts of the bridge shall be held in close contact with the pole faces. The remaining space between the end parts of the bridge and the pole faces shall be filled with a small amount of high vacuum silicone grease whilst keeping the top surface of the bridge strip flat. In order to prevent a formation of large cavities, the grease should be spotted on the pole face in a grid pattern, the bridge is placed, and pressed firmly from the top of a flat glass plate placed on the bridge. Care shall be taken not to stain the surface of the low friction film with grease. The bridge shall be replaceable in order to maintain the smooth surface condition (see 4.3.4 and Clause A.8).

NOTE 2 High vacuum silicone grease has the appropriate properties being chemically inert, having low vapour pressure, and being difficult to solidify for a long time. However, if the grease stains the surface of the low friction film and/or the back surface of the test specimen, the frictional force acting on the test specimen increases and the magnetostriction value decreases. Grease stains can be removed with acetone.

NOTE 3 An H coil with the same length as the secondary coil can be embedded in the bridge inside the secondary winding in order to detect the magnetic field strength $H(t)$ applied to the test specimen. This is useful to investigate magnetostriction characteristics of grain-oriented electrical steel.

The test specimen shall be placed on the bridge so that the axis of the test specimen is coincident with the horizontal axis of symmetry of the winding former (hereafter, simply called “the axis of the winding former”).

NOTE 4 Misalignments of the test specimen can cause lateral vibrations of the test specimen by the Maxwell force, which works to align the axes of the test specimen and the winding former, causing measurement offsets.

Both ends of the test specimen shall overhang the bridge (see Clause A.6). The parts of the test specimen situated outside the pole faces shall be no longer than a few mm (see Clause A.7). The end of the test specimen opposite to the clamp shall be free to move. Nothing shall be connected to this end (see Clause A.7). The other end of the test specimen shall make contact with the end stop over the full width.

During the measurement, the test specimen shall be fixed to the test apparatus by means of the clamp block and the weight (see 4.3.7). The side of the clamp block facing the optical sensor shall be in plane with the inner edge of the pole face (see Figure 2 and Clause A.2).

No weight, except the optical target, shall be placed on the test specimen between the end of the test specimen opposite the clamp and the clamp block (see Clause A.5) [12].

The optical target shall be placed on the test specimen inside the winding former so that the distance between the optical target centre and the inner edge of the pole face is $10 \text{ mm} \pm 1 \text{ mm}$ when the test specimen is placed on the bridge (see Figure 2 and 4.3.5).

NOTE 5 If the optical target is located close to the pole face, out-of-plane vibrations of the test specimen on the pole face can cause measurement offsets (see Clause A.2).

The optical sensor shall be placed in the optimum position so as to maximize the signal to noise ratio of the output signal. The laser beam shall be parallel to the axis of the winding former within $\pm 0,1^\circ$ in order to prevent measurement offsets due to vertical and lateral vibrations of the test specimen.

NOTE 6 The optical sensor has optimum distances from the optical target to maximize the signal to noise ratio of the output signal. The optimum distances are usually specified in the instruction manual of the optical sensor.

NOTE 7 The inclination of the laser beam can be adjusted so that the displacements of the laser beam from the axis of the winding former at both ends of the winding former are the same within $\pm 0,7$ mm.

The laser beam position on the optical target should be adjusted to maximize the intensity level of the reflected laser beam detected by the optical sensor in order to increase the signal to noise ratio of the output signal. The optical sensor should be mounted on an external positioner in order to make it easier to adjust the laser beam position (see Figure 2).

The base length of the magnetostriction measurement is the distance along the axis of the winding former between the optical target centre and the side of the clamp block facing the optical sensor (see Figure 2).

The auxiliary support structures close to the magnetic circuit shall be non-magnetic. Care shall be taken to avoid an electrical short circuit around the magnetic flux through the magnetic circuit.

All items placed on the vibration-free table should be stabilized to the table in order to prevent unexpected resonance generation and vibration transmission to the test apparatus.

The test apparatus should be located away from external noise. The test apparatus shall not be touched by hand or tools during the measurement, otherwise it induces vibration of the test apparatus causing, in turn, measurement offsets. The test apparatus should be placed so that the axis of the winding former is approximately at right angles to the direction of the earth's magnetic field (see Clause A.4).

NOTE 8 A simple magnetic shield and a windshield covering the test apparatus can weaken the influence of the external magnetic and acoustic noises respectively.

It is fundamentally important that the surface on which the test specimen is placed is flat and clean in order to stabilize the frictional force acting on the test specimen to low values (see Clause A.5). A flat glass plate shall be used to check and maintain the flatness (see 4.3.2, 4.3.4 and 4.3.9).

The test apparatus shall be verified so that there is no out-of-plane vibration of the test specimen and no effect of resonance causing measurement offsets (see Clause A.8).

4.2 Test specimen

The test specimen shall be rectangular and flat. The test specimen shall be free of fold marks, dents and scratches with residual stress. The back surface of the test specimen shall be free of substances that affect friction such as grease, adhesives, liquids, powders, etc. (see Clause A.5).

The length and width of the test specimen shall be $500 \text{ mm} \pm 0,5 \text{ mm}$ and $100 \text{ mm} \pm 0,2 \text{ mm}$ respectively.

The test specimen shall be cut parallel to the direction of rolling unless otherwise specified.

The test specimen shall be cut without forming excessive burrs and mechanical distortion. Stresses introduced into the test specimen by the cutting process shall be as low as possible. The test specimen shall be handled very carefully in order to avoid any further introduction of stresses.

NOTE 1 The stress introduced into the test specimen can create 90 degree magnetic domains in the material causing magnetostriction offsets.

NOTE 2 A laser cutting technique can be used provided that the comparability of the results is demonstrated. It can leave a considerable amount of stress along the cut edges [6].

When a test specimen is being cut, the edge of the parent strip is taken as the reference direction. The angle between the reference direction and the cutting direction shall be within $\pm 1^\circ$.

4.3 Test apparatus

4.3.1 General

The components of the test apparatus shall be assembled with minimal misalignment in order to prevent measurement offsets. In particular, the flatness of the surface on which the test specimen is placed shall be ensured.

In order to prevent resonance with the harmonic components of magnetostriction strain, the test apparatus shall be free from natural frequencies between 50 Hz and 1 000 Hz (see Clause A.7).

4.3.2 Yoke

The yoke should have a low residual magnetization and a low reluctance. The yoke shall be fixed to the test apparatus so that the two pole faces are in the same horizontal plane.

NOTE 1 That the two pole faces are in the same horizontal plane can be confirmed by the fact that when a liquid such as alcohol is dropped on the pole faces and the glass plate is placed on top, a thin film of the liquid spreads uniformly over the entire pole faces. A difference in height and/or an inclination between the two pole faces can cause deformation of the bridge strip and measurement offsets (see Clause A.6).

NOTE 2 Due to the elastic deformability of the yoke, the two pole faces can be no longer in the same plane depending on how the yoke is fixed, even if the yoke alone was processed so that the two pole faces are in the same plane.

Care shall be taken to avoid a deterioration of the magnetic properties of the yoke due to excessive stress and to prevent vibration of the yoke during magnetization. The yoke should be fixed rigidly to the vibration-free table, or the rigid base plate, at points close to the pole faces so that it will not be displaced by the clamping force. The outside dimension of the yoke along the axis of the winding former shall be slightly shorter than 500 mm; between 494 mm and 496 mm is recommended.

The yoke may be a vertical single yoke or a horizontal double yoke (see Figure 3). Other types of yoke may be used provided that no stress is applied to the test specimen due to the yoke, and that the comparability of the results is demonstrated.

The vertical yoke shall have two pole faces having a length of $25 \text{ mm} \pm 1 \text{ mm}$ along the axis of the winding former and a width between 105 mm and 110 mm. The height of the yoke shall be between 80 mm and 90 mm.

The horizontal yoke shall have two pole faces having a length between 50 mm and 60 mm along the axis of the winding former and a width between 400 mm and 500 mm. The height of the yoke shall be around 10 mm.

Other dimensions of the yoke may be applicable provided that the comparability of the results is demonstrated.

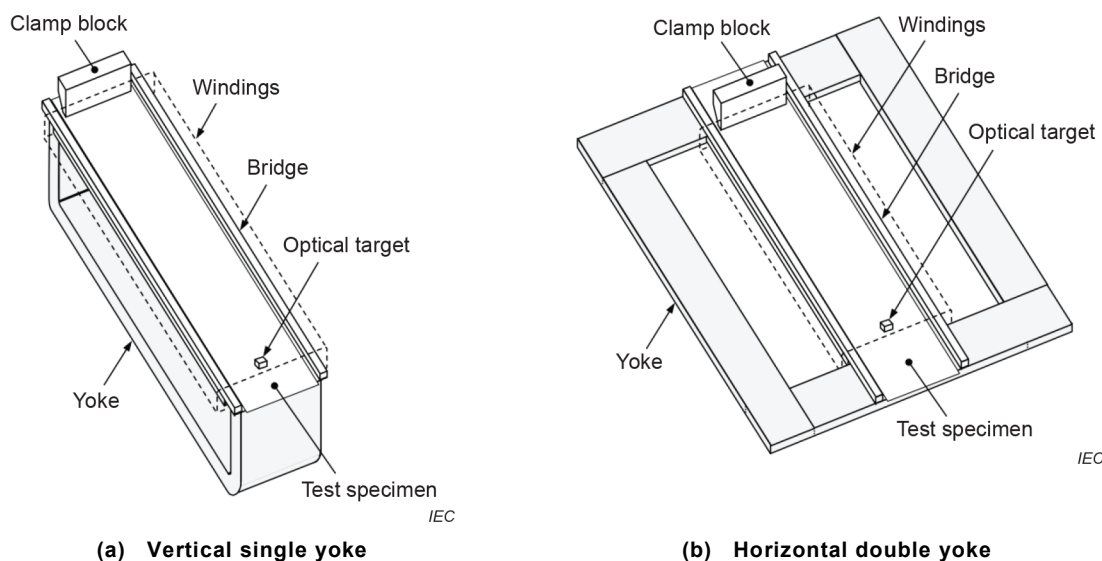


Figure 3 – Schematic diagram of test frames with different types of yoke

NOTE 3 It was confirmed by experiments that the difference in measurement results when a vertical yoke is replaced with a horizontal yoke is sufficiently small in comparison to the reproducibility of the measurement required in this document [3].

The yoke may be made of a glued stack or a C-core of high permeability grain-oriented electrical steel sheets. In the case of the glued stack, the corners shall have staggered butt joints. In the case of horizontal yoke, the sheets should be laminated on a flat plate with sparsely distributed particles of glue on one side of each sheet to minimise stress introduction caused by the gluing.

The yoke shall be carefully demagnetized before use. For the demagnetization of the yoke, an exciting winding shall be wound around the yoke. The demagnetization shall be made without the test specimen in the test apparatus and by slowly decreasing an AC current flowing through the exciting winding to zero, starting from the current that produces a magnetic field in the yoke well above the knee of the magnetization curve of the yoke material. The demagnetized state can be verified by whether the positive and negative peak values of the magnetization current of the test specimen match at the measurement of magnetostriction (see Clause A.3). In the case of the vertical single yoke, a flux closure of the same dimensions as the yoke, e.g. the upper yoke, should be put on the two pole faces during the demagnetization.

NOTE 4 The residual magnetization of the yoke can cause asymmetrical butterfly loops and thus cause measuring offsets.

A vertical double yoke may be applicable provided that the upper yoke does not affect the length change of the test specimen and does not disturb the laser beam path between the optical sensor and the optical target.

NOTE 5 The vertical double yoke is suitable for general loss measurements by the magnetizing current method provided that the bridge is removed and the upper and lower yokes are in contact with the test specimen. The H coil method using an H coil embedded in the bridge inside the secondary winding enables simultaneous measurements of magnetostriction and loss regardless of the yoke type. For the H coil method, see IEC 60404-16:2018 [7].

4.3.3 Windings

The primary and secondary windings shall be wound around the winding former. The winding former shall be non-conducting and non-magnetic. The dimensions of the winding former shall be as follows (see Figure 4):

- length: as long as possible between the two pole faces;
- internal width: wider than the width of the bridge, 120 mm is recommended;
- internal height: higher than the height of the bridge, 15 mm is recommended;
- external height: ≤ 20 mm.

Dimensions in millimetres

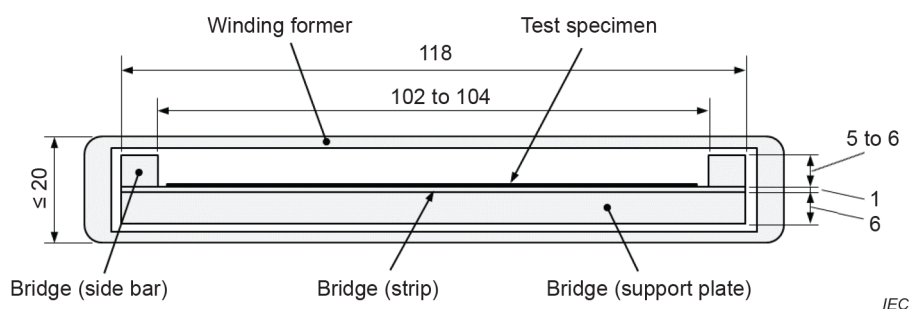


Figure 4 – Cross-section of the winding former and the bridge (schematic)

The primary winding shall be wound homogeneously as long as possible on the winding former. Parts of the winding former flanges in contact with the primary winding should be as thin as possible provided that it can hold the winding former. Care shall be taken to avoid a deformation of the winding former due to tension when winding a copper wire around it.

NOTE 1 The primary winding can be constructed from a single continuous and uniform coil made up of a copper wire 1 mm in diameter wound turn by turn. The winding former thickness can be thinner by using a self-supporting type of coil for the primary winding.

The secondary winding shall be wound on the centre part of the winding former under the primary winding over a half-length of the primary winding to avoid influence of the stray magnetic flux in the areas close to both ends of the primary winding.

NOTE 2 The stray magnetic flux increases as the distance between the test specimen and the pole face increases.

The number of turns of the secondary winding depends on the characteristics of the measuring instruments.

NOTE 3 The secondary winding can be constructed from a single continuous coil made up of copper wire 0,3 mm in diameter wound evenly at intervals.

Care shall be taken to suppress vibration of the primary winding with the AC magnetizing current flowing.

NOTE 4 The vibration of the primary winding can be suppressed by supporting the windings from below in several points along the length.

4.3.4 Bridge

The bridge is the most important component of the test apparatus from the mechanical aspect. The bridge shall be sufficiently rigid so that the test specimen placed on it is kept flat during the measurement. The natural frequencies of the bridge evaluated by structural calculations shall be higher than 1 200 Hz in order to prevent resonance with the harmonic components of magnetostriction strain of up to 1 000 Hz.

The bridge shall be constructed from four parts; a bridge strip, a support plate and two side bars (see Figure 2, Figure 3 and Figure 4). The four parts shall be made of epoxy glass of the same grade. Other non-conducting and non-magnetic materials may be used provided that the rigidity of the bridge is equal to, or better than, that made of epoxy glass. Some or all of the four parts may be cut out from a block of epoxy glass provided the shape of each part is not distorted.

Dimensions of each part of the bridge shall be as follows:

- the bridge strip: 1,0 mm in nominal thickness, 118 mm $\pm$ 0,2 mm in width and the same length as the outside dimension of the two pole faces.

- the support plate: 6 mm $\pm$ 0,2 mm in thickness, the same width as the bridge strip and slightly shorter than the inner distance of the pole faces;
- the side bars: 5 mm to 6 mm in thickness, 7 mm to 8 mm in width and the same length as the bridge strip.

NOTE 1 A thicker bridge strip can increase the stray magnetic flux in the area near the pole faces and a thinner bridge strip can be easily deformed by stress during processing or use.

Protrusions on both surfaces of the bridge strip and surfaces of the other parts where they are to be joined shall be removed before assembly.

It is recommended to make one or several windows or grooves parallel to the length in the centre of the support plate to reduce the weight of the bridge, provided that the rigidity of the bridge is sufficient to keep the test specimen placed on it flat. This is in order to prevent deformation of the bridge over time by the weight. The total width and length of the windows or grooves shall be less than one half of the width of the support plate and two thirds of the length of the support plate respectively. An H coil and/or an air flux compensation coil may be embedded to the windows or grooves of the support plate.

NOTE 2 The method of reducing weight with respect to rigidity is the same as for architectural bridges, based on the fact that the rigidity of a plate is proportional to the cube of the plate thickness.

The parts of the bridge shall not be deformed and the surfaces shall be smooth. The four parts of the bridge shall be closely joined to each other symmetrically as shown in Figure 2, Figure 3 and Figure 4 whilst maintaining the flatness of the bridge strip. These parts may be joined using a thin double-sided adhesive tape and high strength engineering plastic screws may be used if necessary.

The low friction film shall be adhered to the centre of the bridge strip width over the entire length of the bridge strip without dust or air pockets under the film. The low friction film shall be a thin fluorine resin-impregnated glass cloth adhesive film (see Clause A.5). Other types of film may be used provided that the comparability of the results is demonstrated. The thickness of the film shall be thinner than 0,15 mm and the width shall be 95 mm $\pm$ 1 mm in order to prevent an interaction with the edges of the test specimen. Care shall be taken not to distort the bridge strip when applying the film.

Care shall be taken to flatten protrusions on the film surface with a suitable roller, and to remove the edge burrs of the film and adhesive remaining on the film surface.

The bridge strip can deform over time due to the residual stress inside the bridge. It is recommended to leave the glass plate as a weight on the bridge strip while the test apparatus is not being used over a long period in order to prevent this deformation.

In order to maintain the smooth surface condition, the low friction film shall be replaced or the entire bridge shall be replaced before the surface of the film is worn out or severely damaged over time (see Clause A.8).

4.3.5 Optical sensor

The optical sensor shall be a laser Doppler vibrometer. Other types of optical sensor may be used provided that the compatibility of the results is demonstrated.

The optical sensor shall have a resolution of 0,01 μ m or better for a sinusoidal displacement of the optical target at a frequency of 100 Hz. The measurement range of the optical sensor shall be highly sensitive as long as the output signal does not overrange, including noise components. Typical velocity range is $\pm$ 10 mm/s, $\pm$ 20 mm/s or $\pm$ 50 mm/s at full scale output.

NOTE 1 The resolution of 0,01 μm in the displacement of the optical target corresponds to a resolution of 0,023 $\mu\text{m/m}$ of magnetostriction strain when the base length is 436 mm.

In order to analyse the harmonic components of the magnetostriction strain, the frequency band of the optical sensor shall be wider than the range of 50 Hz to 1 200 Hz.

The signal response of the optical sensor shall be sufficiently fast. Any filter function provided in the optical sensor shall not be used unless the comparability of the results is demonstrated.

NOTE 2 The filter functions of the optical sensor can increase the output signal delay. The output signal delay of the optical sensor can be compensated by digital means. Calibration aspects are dealt with in Clause A.8.

The optical sensor shall be verified so that a measurement of a symmetrical displacement of a calibration exciter results in a symmetrical output signal without an offset.

NOTE 3 Odd component noise synchronized to the power frequency superimposed on the output signal of the optical sensor can cause asymmetrical butterfly loops.

NOTE 4 There are two types of laser Doppler vibrometer. One type measures the velocity of the optical target using a single laser beam with a reference point inside the sensor, and the other type measures the differential velocity between the optical target and a reference point on the test frame using two laser beams. The latter type has the advantage of cancelling out a relative motion between of the optical sensor and the test frame.

4.3.6 Optical target

The optical target shall be a small, light and rigid block made of a non-conducting and non-magnetic material, e.g. resin. The mass of the optical target shall be less than 0,2 g.

NOTE 1 A conducting material can be vibrated by the Maxwell force synchronized with the applied AC magnetic field. A massive optical target can cause inertial delay of the movement relative to the test specimen and out-of-plane resonance in the joint system of the optical target and the test specimen (see Clause A.7).

The dimensions of the optical target shall be a height of 3 mm or less, a width of 5 mm $\pm$ 0,5 mm and a length of 4 mm to 5 mm. Other dimensions of the optical target may be applicable provided that the comparability of the results is demonstrated.

NOTE 2 An optical target with increased height can increase measurement offset when tilted. If the bottom area is too small, the optical target can wobble due to poor adhesion.

The side of the optical target facing the optical sensor shall reflect the laser beam as brightly as possible. A reflective tape with glass beads, such as those used for road traffic signs, may be used on this side.

The optical target shall be adhered on the test specimen, for example, by means of a thin double-sided adhesive tape (see 5.2). The optical target with the adhesive tape may be used multiple times by storing it on a non-adherent surface provided that there is no poor adhesion to the test specimen. The number of re-uses should be limited, e.g. 10 times.

NOTE 3 If the test specimen has been wrapped in a rust preventive paper for a long time, the vaporized rust inhibitor can absorb into the surface of the test specimen, making it difficult for the optical target to adhere. If the adhesive cannot be restored even if the surface is cleaned, the optical target can be adhered on an approximately 10 mm square thin plastic tape attached to the surface of the test specimen.

4.3.7 Clamp

The clamp shall consist of the clamp block, the weight and a mechanism to raise and lower them. The clamp block shall press the test specimen vertically with a force applied by the weight during the measurement (see Figure 2). The weight shall be non-magnetic. The clamping force shall be between 15 N and 20 N.

NOTE 1 It was confirmed by experiment that a clamping force of up to 47,5 N does not influence the measurement [4]. However, if the bottom face of the clamp block is slightly inclined to the surface of the test specimen, a concentrated clamping force can introduce excessive stress in the test specimen which can cause measurement offsets.

The clamp block shall be rigid enough to withstand the clamping force. The lower part of the clamp block shall be non-conducting and non-magnetic to at least 10 mm thickness. The bottom face of the clamp block shall have a large friction coefficient which is sufficient to hold the test specimen against the magnetostriction force. Other parts of the clamp block shall be non-magnetic.

NOTE 2 The test specimen is held by the frictional forces, which is in proportion to the clamping force.

The width of the bottom face shall be $95 \text{ mm} \pm 1 \text{ mm}$ in order to avoid an interaction with the edges of the test specimen. The length of the bottom face along the axis of the winding former shall be $5 \text{ mm} \pm 1 \text{ mm}$. The bottom face shall be parallel with the top of the bridge strip (see Clause A.5).

The mechanism to raise and lower the clamp block shall move the clamp block smoothly with a linear guide, e.g. a stage held by linear ball guides, to bring the clamp block into close contact with the test specimen over the whole bottom face without an impact. The linear guide shall be fixed vertically to the test apparatus. The clamp block shall evenly press the test specimen against the pole face with the specified clamping force.

NOTE 3 The linear guide prevents the clamp block from moving horizontally.

NOTE 4 If the clamping force applied to the test specimen is not uniform in the width direction, it can cause lateral vibration of the test specimen and measurement offsets. If the clamping force is much lower than the specified value, the longitudinal vibration of the test specimen due to magnetostriction can be damped and harmonic components of the vibration can decrease.

When loading and unloading the test specimen in and out of the winding former, the clamp block and the weight are raised up.

4.3.8 End stop

The end stop shall be non-magnetic and conductive in order to ground the electrical charge on the test specimen (see Clause A.6). An electric wire shall be connected between the stop end and the grounded vibration-free table. The end stop should be of the same width as the test specimen.

The side of the end stop facing the end of the test specimen shall be perpendicular to the axis of the winding former (see Figure 2).

The end stop shall be supported on a vertical swivel shaft fixed to the test apparatus in order to make contact with the end face of the test specimen over the full width, even if the end of the test specimen is not exactly cut perpendicular to the longitudinal edge of the test specimen. The end stop may be retracted downward in order easily to load and unload the test specimen in and out of the winding former.

NOTE The end stop can be a brass or aluminium plate fixed to the shaft of a single-pull-action air cylinder.

4.3.9 Flat glass plate

The flat glass plate shall be a float-made glass plate, such as those used for windows and mirrors. The dimensions of the flat glass plate shall be a nominal thickness of 5 mm or 6 mm, a length of $500 \text{ mm} \pm 1 \text{ mm}$ and a width of $100 \text{ mm} \pm 1 \text{ mm}$.

NOTE The flatness of a glass plate can be verified by reflecting sunlight and checking that the shape reflected on the wall or ceiling parallel to the glass plate is the same as the glass plate.

The flat glass plate is used to verify whether the two pole faces are in the same plane and the flatness of the bridge strip (see 4.3.2 and 4.3.4). In addition, the flat glass plate is also used as a weight left on the top of the bridge strip when the test apparatus is not being used over a long period (see 4.3.4).

4.4 Air flux compensation

Compensation of the effect of air flux on the induced secondary voltage shall be made. This may be achieved, for example, by using a mutual inductor or by digital means described in Annex C.

The mutual inductor shall be isolated from the test apparatus to prevent interference between the leakage magnetic flux from the mutual inductor and the test apparatus (see Clause A.4).

4.5 Power supply

The power supply shall consist of a computer-controlled arbitrary signal generator and a power amplifier, or an instrument integrating both of these functions.

The arbitrary signal generator shall synthesize a magnetizing signal of waveform, amplitude and frequency, which are programmed externally, so that the waveform of the compensated induced secondary voltage is sinusoidal.

The waveform of the compensated induced secondary voltage shall be maintained sinusoidal during the measurement. This may be achieved by various means, for example by digital means described in Annex D.

In order to ensure that only the fundamental component is present, the form factor of the induced secondary voltage shall be maintained at 1,110 7 within $\pm 0,2$ % or better, and the total harmonic distortion of the compensated induced secondary voltage of up to 1 000 Hz should be less than 1 % (see Clause A.3).

NOTE The total harmonic distortion can be calculated as the ratio of the sum of RMS amplitudes of harmonics of up to 1 000 Hz to the amplitude of the fundamental frequency.

The power amplifier shall be of low internal impedance, high voltage and frequency stability and sufficiently low voltage noise. The output voltage and frequency shall be maintained constant within $\pm 0,2$ % during the measurement.

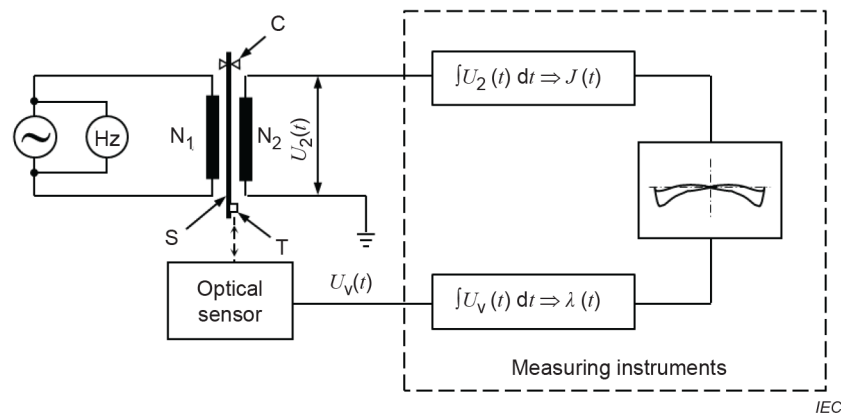
In order to avoid a DC bias of magnetization, DC and even harmonic components in the voltage applied on the primary winding shall be negligible (see Clause A.3).

The power amplifier should be a bipolar type with sufficiently wide frequency and voltage bands for the measurement. Provided it has no adverse influence on the feedback loop process, an isolation transformer may be inserted between the power amplifier and the primary winding in order to match impedance between the power supply output and the primary winding, to remove the DC component of the magnetizing voltage and to suppress voltage noise on the primary winding. The isolation transformer should be demagnetized before use.

4.6 Measuring instruments

The fundamental circuit of the measuring system is illustrated in Figure 5. The function of air flux compensation is not presented in Figure 5, but it is included in the circuit or in the software (see 4.4 and Annex C).

The frequency meter may be removed from the circuit provided that the power supply is controlled by a quartz time keeping device. The instruments to measure magnetic field strength $H(t)$ applied to the test specimen may be added to the circuit; e.g. a current measuring device connected in series with the primary winding or an H coil embedded in the bridge inside the secondary winding.

**Key**

~	power supply
Hz	frequency meter
N_1	primary winding
N_2	secondary winding
S	test specimen
T	optical target
C	clamp
$U_2(t)$	voltage induced in the secondary winding
$U_v(t)$	output voltage of the optical sensor
$\int U_2(t) dt \Rightarrow J(t)$	J -integrator function of software
$\int U_v(t) dt \Rightarrow \lambda(t)$	λ -integrator function of software

Figure 5 – Fundamental circuit of the measurement system

The measuring instruments usually consist of a calibrated digitizer and a digital signal calculator (usually a computer), or an instrument integrating both of these functions.

The digitizer shall have several independent signal channels of voltage inputs. The number of channels should be three or more for signals of $U_2(t)$, $U_v(t)$ and $H(t)$.

The signal channels shall have sufficiently high input impedances (typically $> 1 \text{ M}\Omega$ in parallel with about 100 pF). Input signals should be amplified before digitizing to ensure at least a 12-bit resolution for the given amplitude of input voltage in order to reduce the digitizing error. Resolution of the analogue-digital convertor should be a 16-bit resolution or more at full scale.

The signal channels shall work simultaneously with a sampling clock synchronized with the readout clock of the arbitrary signal generator. An unsynchronized digitizer may be used provided that the comparability of the results is demonstrated.

The sampling frequency of the digitizer should be a multiple of the magnetizing frequency (Nyquist condition) and sufficiently large to reduce the digitizing error. In order to reduce noise on the signals efficiently, it is recommended that the sampling frequency is as high as the devices allow at measurement and then averaged down to a sampling frequency sufficient for recording. The number of samples per period of magnetization should be a multiple of the power of 2. It is convenient to use digital data processing functions such as integration, Fast Fourier Transform (FFT) and band-pass filter. In order to correct phase differences between the signal channels, the sampling frequency should be 4 096 or more samplings per period of magnetization.

NOTE 1 For recording the wave signals, a reduced data set of 1 024 samplings per period of magnetization is sufficient. If the sampling frequency is an exact multiple of the magnetizing frequency (Nyquist condition), the sampling frequency can be even considerably lower (e.g. 128 samplings per period, see IEC 60404-2:1996/AMD1:2008, Annex A [8]).

The digitizer should create the digital feedback signal to feed into the arbitrary signal generator for the sinusoidal waveform control of the compensated induced secondary voltage by digital means (see Annex D).

The digitizer shall be calibrated and the amplitude and phase differences between the signal channels should be compensated by digital means.

NOTE 2 Calibration aspect is dealt with in Clause A.8.

The digital signal calculator (usually a computer) shall calculate magnetic characteristics and magnetostriction characteristics through the evaluating software with the digital data processing functions of integration, FFT and band pass filter.

5 Measurement procedure

5.1 Principle of measurement

The back surface of the test specimen and the surface of the low friction film shall be free of substances that affect friction (see Clause A.5).

The measurements shall be made at an ambient temperature of $(23 \pm 5) ^\circ\text{C}$ on the test specimen which has first been demagnetized.

The test apparatus and the measuring instruments shall be connected as shown in Figure 5.

The following signals shall be digitized simultaneously and recorded with an uncertainty of $\pm 0,1 \%$ or better:

- voltage induced in the secondary winding $U_2(t)$;
- output voltage of the optical sensor $U_V(t)$.

Synchronous averaging of the signals shall be carried out over a large number of periods, e.g. 64 or 128, to remove unsynchronized noise on the signals.

The data set of signals $U_2(t)$ and $U_V(t)$ provide the complete information for one measurement.

The magnetic polarization $J(t)$ is calculated from $U_2(t)$ (see 6.1) and the magnetostriction strain $\lambda(t)$ is calculated from $U_V(t)$ (see 6.2).

The butterfly loop is determined by $J(t)$ and $\lambda(t)$ (see 6.3) and the peak-to-peak value λ_{p-p} and the zero-to-peak value λ_{0-p} are determined from $\lambda(t)$ (see 6.4).

5.2 Preparation of measurement

At the beginning of the measurements, the surface of the low friction film shall be wiped with a non-woven fabric soaked in a small amount of suitable solvent, e.g. acetone, in order to remove friction-altering substances such as grease, adhesives, liquids, powders, etc. (see Clause A.5).

If there is a friction-altering substance on the back surface of the test specimen, it shall be wiped off with a non-woven fabric soaked in a small amount of suitable solvent, e.g. acetone, before the measurement (see Clause A.5).

The length of the test specimen l shall be measured with an uncertainty of $\pm 0,1$ % or better. The mass of the test specimen m shall be determined with an uncertainty of $\pm 0,1$ %.

Test specimens shall be in good condition and representative of the material to be tested. If any unusual features, e.g. non-flatness, uneven appearance, scratches and deformations, that can be caused by handling or cutting, are found on the test specimen, it shall be reported in the test report.

The cross-sectional area of the test specimen A shall be calculated by Formula (1).

$$A = \frac{m}{l\rho_m} \quad (1)$$

where

A is the cross-sectional area of the test specimen, in square metres;

m is the mass of the test specimen, in kilograms;

l is the length of the test specimen, in metres;

ρ_m is the conventional density of the grain-oriented electrical steel specified in IEC 60404-8-7, in kilograms per cubic metres, equal to $7\,650\text{ kg}\cdot\text{m}^{-3}$.

The optical target shall be mounted on the test specimen outside the test apparatus before the measurement. The position of the optical target on the test specimen shall be on the axis of the test specimen and at a predetermined distance from the edge of test specimen. The distance shall be determined so that the distance between the optical target centre and the side of the clamp block facing the optical target is the same as the prescribed base length when the test specimen is set on the bridge (see Figure 2).

NOTE 1 The mounting of the optical target on the test specimen is made easier by using a test specimen preparation table with a scale or a pointer indicating the mounting position of the optical target relative to the end of the test specimen.

The test specimen with the optical target shall be set on the bridge (see 4.1). During the setting process, the test specimen may be placed on a thin resin sheet to prevent wear on the surface of the low friction sheet; the thin resin sheet shall be withdrawn after the process.

The position of the test specimen placed on the bridge shall be adjusted so that the axis of the test specimen aligns with the axis of the winding former within $\pm 0,2$ mm. The end of the test specimen shall make contact with the end stop over the full width (see Figure 2).

NOTE 2 The positioning of the test specimen is made easier by using a side-positioning tool which aligns both longitudinal edges of the test specimen symmetrically to the axis of the winding former, and by using a pusher which can push the test specimen gradually towards the end stop (see Clause B.3). These tools are removed before the measurement is taken.

The test specimen shall be fixed to the test apparatus by means of the clamp block and the weight.

The focus and position of the laser beam on the optical target shall be adjusted to maximize the intensity level of the reflected laser beam detected by the optical sensor. A lower height of the laser beam on the optical target is preferable in order to suppress measurement offsets if the optical target tilts. The laser beam position shall be fixed during the measurement.

Before the measurement, the test specimen shall be carefully demagnetized in the test apparatus by slowly decreasing an AC magnetic field, starting from well above the value to be measured and the knee of the magnetization curve.

NOTE 3 Whether the test specimen is effectively demagnetized can be confirmed by matching the positive and negative peak values of the magnetizing current at the measurement of magnetostriction (see Clause A.3).

5.3 Adjustment of power supply

In practice, single or grouped peak values of magnetic polarization $\hat{J}$ at a specified magnetizing frequency shall be decided in advance. The measurement shall be carried out continuously in ascending order of the peak values of magnetic polarization $\hat{J}$.

The output of the power supply shall be slowly increased until the peak values of magnetic polarization $\hat{J}$ has reached the prescribed value. The output of the power supply shall not be decreased during the measurement sequence except for negligible modifications.

The waveform of the compensated induced secondary voltage $U_2(t)$ shall be maintained sinusoidal at a form factor of 1,110 7 within $\pm 0,2$ % or better and the total harmonic distortion of the compensated induced secondary voltage $U_2(t)$ of up to 1 000 Hz should be less than 1 % during the measurement (see 4.5).

If the test specimen buzzes during the measurement, it shall be reported as an unusual feature in the test report.

NOTE The buzz is caused by severe out-of-plane vibration of the test specimen on the pole face. In this case, the results are usually incorrect (see Clause A.6).

6 Determination of characteristics

6.1 Determination of the magnetic polarization $J(t)$

The magnetic polarization $J(t)$ shall be calculated by Formula (2).

$$J(t) = \frac{1}{N_2 A} \left\{ \int_0^t U_{2c}(\tau) d\tau - \frac{1}{T} \int_0^T \left(\int_0^t U_{2c}(\tau) d\tau \right) dt \right\} \quad (2)$$

where

$J(t)$ is the magnetic polarization, in teslas;

N_2 is the number of turns of the secondary winding;

A is the cross-sectional area of the test specimen, in square metres;

$U_{2c}(\tau)$ is the compensated induced secondary voltage, in volts;

T is the length of the period of magnetization, in seconds;

t is a time variable, in seconds;

τ is an auxiliary time variable, in seconds.

The second term in the brackets of Formula (2) is the time average over the length of a period of magnetization which compensates for the integration constant.

6.2 Determination of the magnetostriction strain $\lambda(t)$

The magnetostriction strain $\lambda(t)$ shall be calculated by Formula (3).

$$\lambda(t) = \frac{1}{k_v l_0} \int_0^t U_v(\tau) d\tau - \lambda_0 \quad (3)$$

where

$\lambda(t)$ is the magnetostriction strain, in $\mu\text{m/m}$;

$U_V(\tau)$ is the output voltage of the optical sensor, in volts;

k_V is the sensitivity of the optical sensor, in volts second per metre;

l_0 is the base length of the magnetostriction measurement, in metres (see Figure 2);

λ_0 is a calibration value so that the average of the magnetostriction strain $\lambda(t)$ at two zero magnetic polarizations in a period of magnetization is zero, in $\mu\text{m/m}$;

t is a time variable, in seconds;

τ is an auxiliary time variable, in seconds.

If the output of the optical sensor is in a displacement mode and $U_V(t)$ is in proportion to the displacement of the optical target, the integral part $\int_0^t U_V(\tau) d\tau$ of Formula (3) shall be replaced by $U_V(t)$, and the unit of k_V becomes volts per metre.

6.3 Determination of the butterfly loop

The butterfly loop shall be determined by drawing a closed two-dimensional curve with the magnetostriction strain $\lambda(t)$ as the vertical axis and the magnetic polarization $J(t)$ as the horizontal axis for a period of magnetization.

Before drawing the curve, noise on $\lambda(t)$ and $J(t)$ signals should be smoothed out by digital means; e.g. weighted time moving averaging or band pass filtering.

6.4 Determination of the peak-to-peak value λ_{p-p} and the zero-to-peak value λ_{0-p}

Before determining the magnetostriction characteristics, the symmetry of the butterfly loop shall be checked. If the butterfly loop is particularly asymmetrical, e.g. if the asymmetry exceeds 2 %, it shall be reported in the test report as an unusual feature.

NOTE 1 Asymmetrical butterfly loops can be caused by many factors; e.g. misalignments of the test apparatus, residual magnetization of the test specimen, residual magnetization of the yoke (see Article A.4), non-flatness of the test specimen, movement of the optical target during the measurement and factors inherent in electrical circuits of the optical sensor.

The peak-to-peak value λ_{p-p} and the zero-to-peak value λ_{0-p} shall be averages of the first and second half values of the period, which correspond to the right and left parts of the butterfly loop (see Figure 1).

NOTE 2 Subsidiary characteristics the velocity level L_V , the A-weighted velocity level L_{VA} , the acceleration level L_a and the A-weighted acceleration level L_{aA} are described in Annex E.

7 Reproducibility of the measurement of the peak-to-peak value λ_{p-p}

The reproducibility of the measurement of the peak-to-peak value λ_{p-p} of this method using the test apparatus defined above is characterized by a relative standard deviation of 2 %, but not less than a standard deviation of 0,02 $\mu\text{m/m}$. This reproducibility value has been estimated on the basis of the results of the international round robin test [4].

NOTE 1 The zero-to-peak value λ_{0-p} can take a positive or negative value. Therefore, its reproducibility of the measurement cannot be characterized by a percentage of relative standard deviation. The standard deviation of the zero-to-peak value λ_{0-p} is usually a little larger than that of the peak-to-peak value λ_{p-p} .

NOTE 2 Annex A provides requirements of the test apparatus to improve the reproducibility of the measurement.

8 Test report

The test report shall include the following, as applicable:

- a) the type and identity of the test specimen;
- b) the number of this document (IEC 60404-17), including the year of publication;
- c) the type of the optical sensor;
- d) the ambient temperature of the test specimen during the measurements;
- e) the magnetizing frequency;
- f) the peak values of magnetic polarization;
- g) the results of measurements, including the graphics of the butterfly loops;
- h) the estimated uncertainty of the measurements;
- i) any deviations from the procedure;
- j) any unusual features observed (see 5.2, 5.3 and 6.4);
- k) the date of the test.

Annex A (normative)

Requirements of the test apparatus for measurements of the magnetostriction characteristics

A.1 General

In order to obtain sufficient reproducibility of the method described in this document, the following shall be applied:

- correct setting of the base length of the magnetostriction measurement;
- strict control of the sinusoidal magnetic polarization;
- isolation of the test apparatus from external noises;
- suppression of the frictional force acting on the test specimen;
- suppression of the out-of-plane vibrations of the test specimen;
- avoidance of resonances in the test specimen and the test apparatus;
- calibration and verification of the test apparatus.

A.2 Correct setting of the base length of the magnetostriction measurement

The base length of the magnetostriction measurement shall be as long as possible within a uniform and unidirectional magnetic field in the longitudinal direction of the test specimen. In order to realise this condition, the primary winding shall be low profile and as long as possible between the two pole faces. The base length is the distance along the axis of the winding former between the optical target centre and the side of the clamp block facing the optical sensor.

The magnetostriction of grain-oriented electrical steel is basically due to volume changes of 90 degree magnetic domains under an applied AC magnetic field [9]. The volume of 90 degree magnetic domains changes due to the changes of the magnetic polarization and the magnetic field. The influence of the magnetic field increases as the magnetic field strength increases and when there is a magnetic field component perpendicular to the surface of the test specimen [1], [10].

Over the part of the test specimen located on the pole face, the magnetic polarization decreases with distance from the inner edge of the pole face as the magnetic flux moves to the yoke. This results in the occurrence of the Maxwell force causing out-of-plane vibrations of the test specimen (see Clause A.6). Therefore, the part of the test specimen located on the pole face shall be outside the base length.

The out-of-plane vibrations of the test specimen excited on the pole face cause alternating bends of the test specimen at the part adjacent to the pole face depending on the amount of air gaps under the test specimen. When the optical target is mounted on this part of the test specimen, the bends cause alternating tilts of the optical target resulting in an alternating change of the length between the optical target and the optical sensor. This can cause measurement offsets depending on the height of the laser beam on the optical target. Therefore, the optical target shall be placed apart from the edge of the pole face by 10 mm [4].

NOTE For example, for a bend of the test specimen with an incline rate of $0,5 \mu\text{m}$ per 10 mm, the length change between the optical target and the optical sensor is $0,1 \mu\text{m}$ when the height of the laser beam is 2 mm on the optical target. This length change corresponds to an apparent magnetostriction of $0,23 \mu\text{m}/\text{m}$ for a base length of 436 mm.

The clamp block shall be placed on the pole face opposite to the optical sensor so that the side of the clamp block facing the optical sensor is in plane with the inner edge of the pole face. This is in order to exclude the part of test specimen on the pole face from the base length and to avoid an occurrence of out-of-plane vibration on the pole face. The clamp block may be placed

between the pole face and the winding former provided that the test specimen does not deform due to the clamping force.

A.3 Strict control of the sinusoidal magnetic polarization

The sinusoidal waveform of the compensated induced secondary voltage shall be controlled more strictly than that required for general loss measurement process in order to accomplish the sinusoidal magnetic polarization in the test specimen.

The harmonic components of magnetostriction strain of the material are affected by not only harmonic components of the magnetic polarization but also harmonic components of the magnetic field strength, especially over the higher magnetic field region.

NOTE 1 The applied magnetic field strength acts on 90 degree magnetic domain walls and can cause volume changes of 90 degree magnetic domains. However, the volume changes of 90 degree magnetic domains cause only a small change of the magnetic polarization along the rolling direction of grain-oriented electrical steel. Therefore, under sinusoidal waveform control, slight harmonics of the induced secondary voltage can cause relatively large harmonics of the magnetic field strength, especially beyond the knee of the magnetization curve.

NOTE 2 There are roughly two types of 90 degree magnetic domains in a grain-oriented electrical steel sheet. One type distributes within 180 degree magnetic domains and the other type transverses 180 degree magnetic domains. These two types of 90 degree magnetic domains have different contributions to magnetostriction.

NOTE 3 In the case that a grain-oriented electrical steel sheet is magnetized in the parallel to the rolling direction, the volume changes of the 90 degree magnetic domains have a small effect on the magnetic polarization. However, in the case that a grain-oriented electrical steel sheet is magnetized in the direction perpendicular to the rolling direction, the volume changes of the 90 degree magnetic domains are closely related to changes of the magnetic polarization when the amount of 90 degree magnetic domains increases beyond a certain level.

For sinusoidal waveform control, it is a necessary condition that the form factor of the compensated secondary voltage is $\pi/2\sqrt{2} \approx 1,110\ 7$, but it is not the only condition since non-sinusoidal waveforms can also produce the form factor of 1,110 7. Waveform control by digital means sometimes enhances higher harmonics due to an accumulation of slight phase mismatches during the iteration of wave form calculation. In order to avoid this situation, the compensated induced secondary voltage shall be sensed without external noise and phase shift as far as possible.

Therefore, not only the form factor but also the total harmonic distortion of the compensated induced secondary voltage shall be checked in order to ensure that only the fundamental component is present (see 4.5). The form factor of the compensated induced secondary voltage shall be maintained at 1,110 7 within $\pm 0,2\ %$ or better and the total harmonic distortion of the compensated induced secondary voltage of up to 1 000 Hz should be less than 1 % [3].

A DC bias of magnetization of the test specimen can increase magnetostriction values. The residual magnetizations of the yoke and/or the test specimen can cause the DC bias of magnetization. The yoke and the test specimen shall be carefully demagnetized taking a sufficient time to decrease the AC magnetic field before the measurement. DC and even harmonic components of the magnetizing current also can cause the DC bias of magnetization. The magnetizing signal supplied to the power amplifier can contain even harmonics due to noise superimposed on the signal line, and cause a difference in positive and negative peak values of the magnetizing current. Even harmonic components in the magnetizing signal shall be removed and the DC component in the magnetizing voltage shall be negligible. In order to ensure that there is no DC bias of magnetization at the measurement, the positive and negative peak values of the magnetization current shall be equivalent.

A.4 Isolation of the test apparatus from external noise

Because the magnetostriction strain of grain-oriented electrical steel is quite small, about 1 $\mu\text{m/m}$ or less, when magnetized in the parallel to the rolling direction, the test apparatus shall be isolated from external noise sources, e.g. vibrational, magnetic, electrical and acoustic noise sources, as much as possible. Especially, those synchronized to the power frequency shall be

isolated because the synchronized noise is usually difficult to remove from the signal of magnetostriction.

NOTE 1 A length change of the test specimen caused by magnetostriction is miniscule; for example, only a $0,04\ \mu\text{m}$ change of a base length of 400 mm due to a magnetostriction strain of $0,1\ \mu\text{m}/\text{m}$. Therefore, external noise can easily cause measurement offsets.

Vibrations transmitted from the floor shall be isolated by placing the test apparatus on a vibration-free table. Vibrations transmitted through cables shall be blocked by stabilizing the cables to the vibration-free table. Wind and acoustic noise from the surroundings should be blocked by a windshield around the test apparatus if they affect the measurement.

NOTE 2 The influence of wind and acoustic noise on the measurement can be verified by observing changes in the output signal of the optical sensor in response to a human voice by means of an oscilloscope. The effects of the windshield can be tested by measurements with and without a simple cover which is constructed from non-magnetic sheets.

The test apparatus can vibrate when touched by hand. Touching the test apparatus with hand or tools during the measurement shall be avoided.

The earth's magnetic field can magnetize the yoke and the test specimen, and can introduce a DC magnetic bias in the magnetic circuit. In order to prevent this, the axis of the winding former shall be approximately at right angles to the direction of earth's magnetic field. Alternatively, a simple magnetic shield around the test apparatus may be used to reduce sufficiently the effects of the external magnetic field on the measurements.

NOTE 3 The effects of the magnetic shield can be tested by measurements with and without a simple cover which is constructed from soft magnetic sheets.

Electromagnetic devices around the test apparatus, e.g. mutual inductors, high current power lines and electromagnetic devices such as motors and transformers, can emit external magnetic field synchronized to the power frequency and can change the magnetic field applied to the test specimen. The mutual inductor for the air flux compensation which leaks magnetic flux to the surroundings shall be isolated from the test apparatus. The test apparatus shall be kept away from electromagnetic devices and high current power lines as much as possible. Alternatively, a simple magnetic shield may cover the test apparatus.

NOTE 4 The leakage magnetic flux from the mutual inductor can be shielded by providing a flux closure made of soft ferrite to the mutual inductor.

The optical sensor shall be placed a little apart from the test specimen and the yoke in order to avoid the influence of the leakage magnetic flux from the magnetic circuit.

Electrical noise superimposed on signal cables can deteriorate the quality of measurements. Noisy $\lambda(t)$ signals can cause increases in the peak-to-peak values λ_{p-p} and the zero-to-peak values λ_{0-p} . In order to reduce the noise on the signal cables, the signal cables connected to the input terminals of the measuring instruments should be isolated from the frame ground. Screened twisted pair cables should be used as the signal cables with the screens of each cable connected to signal ground. Care shall be taken in routing the signal cables to avoid superposition of inductive noise on the signals. In order to prevent superposition of noise on the signals within the measuring instruments, low noise amplifiers and low noise DC power supplies should be used. The measuring instruments and the vibration-free table should be grounded.

Synchronous averaging of the signals shall be carried out over a large number of periods, e.g. 64 or 128, to remove unsynchronized noise from the signals.

When evaluating the harmonic components of magnetostriction, it is necessary to consider the proportions of harmonic noise contained in the magnetostriction signal. The harmonic even components of the magnetostriction in the frequency range of interest shall be sufficiently larger than the adjacent odd harmonic components.

A.5 Control of the frictional force acting on the test specimen

The frictional force acting on the test specimen shall be kept low and constant; otherwise the value of magnetostriction measurement will decrease significantly [12].

There are two cases of frictional involvement: the first case is when the two rubbing surfaces are both flat and clean, and the second case is when at least one surface is non-flat and/or there is contamination on the surface that affects friction.

In the second case, the frictional force acting on the test specimen can increase significantly and the longitudinal vibration of the test specimen due to magnetostriction can be significantly damped. Therefore, it is fundamentally important to ensure that the back surface of the test specimen and the surface on which the test specimen is placed are flat and free from substances that affect friction at the measurement.

Even in the first case, the longitudinal vibration of the test specimen due to magnetostriction can be damped by the frictional force acting on the test specimen depending on the material of the surface on which the test specimen is placed. Therefore, it is important to reduce the strength of the frictional force in order to reduce measurement offsets. The influence of frictional force becomes remarkable in thinner materials and lower magnetostriction materials.

NOTE 1 The magnetostriction force can be considered as equal to the externally applied force that causes the same change in length of the material as the magnetostriction strain. It can be calculated from the zero-to-peak value λ_{0-p} and the Young's modulus of the material. In this case, the Young's modulus can be provided by the manufacturer or measured according to the dedicated ISO Standard. For example, the magnetostriction force of a 0,23 mm thick grain-oriented electrical steel sheet with a Young's modulus of 115 GPa can be estimated at around 0,26 N per 0,1 $\mu\text{m/m}$ of λ_{0-p} .

The frictional force acting on the test specimen is in proportion to the coefficient of friction of the surface where the test specimen is placed and the perpendicular force applied on the surface. Except the optical target, no weight shall be placed on the test specimen between the end of the test specimen opposite the clamp and the clamp block in order to prevent measurement offsets due to the increase of the frictional force [12].

NOTE 2 For example, a frictional force acting on a 0,23 mm thick and 400 mm long grain-oriented electrical steel sheet caused by the weight of the test specimen can be estimated at around 0,35 N for a coefficient of friction 0,5. However, the coefficients of friction given in the literature is when the two surfaces rub against a relatively long distance and may not be applicable when the rubbing distance is as short as 1 μm , as in the case of magnetostriction measurement of the grain-oriented electrical steel in the rolling direction.

A low friction film shall be adhered to the bridge strip where the test specimen is placed in order to reduce the frictional force. Fluorine resin is suitable for the material of the film because it has the lowest coefficient of friction at around 0,1 against steel. However, a thin fluorine sheet is soft and easy to stretch and is difficult to adhere onto the bridge strip without leaving any stress that can distort the bridge strip. Thin fluorine resin-impregnated glass cloth adhesive film is relatively solid and easy to adhere to the bridge strip without leaving stress. The width of the low friction film shall be less than the width of the test specimen in order to prevent interaction with the edge burrs of the test specimen.

NOTE 3 The surface texture of fine irregularities on the fluorine resin-impregnated glass cloth film is convenient to prevent fine dust from accumulating on the contact area to the test specimen and also to reduce the contact area interacting with the surface roughness of the test specimen that can resist length changes of the test specimen.

The low friction film can be worn or damaged over time. The film or the entire bridge shall be replaced if the surface of the film is worn out or severely damaged, see Clause A.8.

The surface of the bridge strip onto which the low friction film is adhered shall be flat without slight steps and protrusions in order to reduce shape-dependent effects of the frictional force acting on the test specimen, and also to avoid air gap formations under the test specimen which can induce out-of-plane vibrations of the test specimen. Protrusions on both surfaces of the bridge strip shall be removed before assembly, for example, by means of a straight edge of a steel plate or fine sandpaper glued to a flat plate.