IEC/TR 62581

Edition 1.0 2010-08

TECHNICAL REPORT

Electrical steel – Methods of measurement of the magnetostriction characteristics by means of single sheet and Epstein test specimens

INTERNATIONAL ELECTROTECHNICAL COMMISSION

PRICE CODE X

ICS 29.030

ISBN 978-2-88912-101-4

® Registered trademark of the International Electrotechnical Commission

CONTENTS

FOREWORD 5
INTRODUCTION 7
1 Scope 8
2 Normative references 8
3 Terms and definitions 8
4 Method of measurement of the magnetostriction characteristics of electrical steel sheets under applied stress by means of a single sheet tester 9
4.1 Principle of the method 9
4.2 Test specimen 11
4.3 Yokes 12
4.4 Windings 13
4.5 Air flux compensation 14
4.6 Power supply 14
4.7 Optical sensor 14
4.8 Stressing device 15
4.9 Data acquisitions 15
4.10 Data processing 16
4.11 Preparation for measurement 16
4.12 Adjustment of power supply 17
4.13 Measurement 17
4.14 Determination of the butterfly loop 20
4.15 Determinations of the zero-to-peak and peak-to-peak values 20
4.16 Reproducibility 20
5 Examples of the measurement systems 20
5.1 Single sheet tester 20
5.2 Epstein strip tester 25
6 Examples of measurement 26
6.1 Magnetostriction without external stress 26
6.2 Magnetostriction under applied stress 27
6.3 Variation of magnetostriction with coating tension 30
6.4 Factors affecting precision and reproducibility 34
6.4.1 General 34
6.4.2 Overlap length between test specimen and yoke 34
6.4.3 The averaging effect on environmental noise 34
6.4.4 Gap between test specimen and yoke 34
6.4.5 Resetting the test specimen 35
7 Methods of evaluation of the magnetostriction behaviour 36
7.1 Relationship between magnetostriction and magnetic domain structure 36
7.2 A simple model of magnetostriction behaviour 37
Annex A (informative) Requirements concerning the prevention of out-of-plane deformations 40
Annex B (informative) Application of retained stress model to measured stress shifts 42
Annex C (informative) A-weighted magnetostriction characteristics 45
Bibliography 48

Figure 1 – Measurement systems for magnetostriction 9
Figure 2 – Section of the test frame; A-A' in Figure 1 10
Figure 3 – Block diagram of the measurement system 10
Figure 4 – Frames with various types of yoke 13
Figure 5 – Base length l_0 for various types of frame (see Figure 4) 18
Figure 6 – Butterfly loop and determinations of zero-to-peak and peak-to-peak values of magnetostriction 20
Figure 7 – Measurement system using a Michelson interferometer; differential measurement [1] 21
Figure 8 – Measurement system using a laser Doppler vibrometer; differential measurement [2], [3], [17] 21
Figure 9 – Measurement system using a laser Doppler vibrometer; differential measurement [4],[5] 23
Figure 10 – Measurement system using a laser displacement meter; single point measurement [7] 23
Figure 11 – Measurement system using a laser displacement meter; single point measurement [6] 24
Figure 12 – Measurement system using a laser Doppler vibrometer; single point measurement [8] 24
Figure 13 – Schematic diagram of an automated system using accelerometer sensors [12] 25
Figure 14 – Example of measured results for high permeability grain-oriented electrical steel of 0,3 mm thick sheet; at 1,3 T, 1,5 T, 1,7 T, 1,8 T and 1,9 T, 50 Hz [2] 29
Figure 15 – Increase in magnetostriction with compressive stress in the rolling direction; at 1,5 T, 1,7 T and 1,9 T, 50 Hz [2] 29
Figure 16 – Typical zero-to-peak magnetostriction versus applied stress for high permeability grain-oriented electrical steel sheet at 1,5 T, 50 Hz [12] 29
Figure 17 – Stress sensitivity of magnetostriction and permeability in a typical fully processed sample [12] 30
Figure 18 – Typical harmonics of magnetostriction versus applied stress for conventional grain-oriented electrical steel at 1,5 T, 50 Hz [12] 30
Figure 19 – Variation of maximum magnetostriction under compressive stress in high permeability grain-oriented electrical steel at 1,5 T, 50 Hz [20] 31
Figure 20 – Variation of maximum magnetostriction under compressive stress in conventional grain-oriented electrical steel at 1,5 T, 50 Hz [20] 31
Figure 21 – Magnetostriction versus stress characteristics in the rolling direction of conventional grain-oriented electrical steel before and after coating removal at 1,5 T, 50 Hz [20] 31
Figure 22 – Magnetostriction versus stress characteristics in the transverse direction of conventional grain-oriented electrical steel before and after coating removal at 1,5 T, 50 Hz [20] 31
Figure 23 – Magnetostriction versus peak value of magnetic polarization for high permeability 0,30 mm grain-oriented electrical steel sheets with three different coatings; external stress was not applied [17] 33
Figure 24 – Magnetostriction versus peak value of magnetic polarization for high permeability 0,30 mm grain-oriented electrical steel sheets with three different coatings; external compressive stress of 3 MPa was applied in the rolling direction [17] 33
Figure 25 – Effects of overlap length on the reproducibility of measurement [4] 34
Figure 26 – Effect of averaging number on reduction of the error caused by the environmental noise [5] 34

Figure 27 – Effect of gap between the test specimen and the yoke on the reproducibility of measurement; the test specimen was reset at every measurement [5] 35

Figure 28 – Effect of reset of the test specimen on the reproducibility of measurement; the gap distance was 1,2 mm [5] 35

Figure 29 – Magnetic domain patterns on a grain-oriented electrical steel sheet [2] 36

Figure 30 – Schematic diagrams for explanation of magnetic domains and magnetostriction [2],[17] 36

Figure 31 – Separation of the different features of peak-to-peak magnetostriction according to the proposed model [27] 38

Figure 32 – Measured peak-to-peak and zero-to-peak magnetostriction of a grain-oriented electrical steel sheet with fitted curves according to the proposed model [27] 38

Figure 33 – Effect of coating tension on $J_m - \lambda_{sp}$ curves; λ_{sp} is the normalized value of zero-to-peak magnetostriction to the value at saturation polarization [17] 39

Figure 34 – Effect of laser irradiation on $J_m - \lambda_{sp}$ curves; λ_{sp} is the normalized value of zero-to-peak magnetostriction to the value at saturation polarization [17] 39

Figure A.1 – Schematic diagram of out-of-plane deformation of test specimen (length l_m) with radius r 41

Figure A.2 – Errors in length change of the test specimen $\Delta l / l_m$ versus out-of-plane deformation distance Δd 41

Figure B.1 – Variation of coating stress with coating thickness for forsterite and phosphate coating [20] 44

Figure C.1 – Frequency response of the acoustic A-weighting filter, specified in IEC 61672-1 45

Figure C.2 – A-weighted magnetostriction acceleration levels of CGO-0,30 mm and HGO-0,30 mm materials 47

Table B.1 – Measured stress shifts for two stage coating removal 43

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTRICAL STEEL – METHODS OF MEASUREMENT OF THE MAGNETOSTRICTION CHARACTERISTICS BY MEANS OF SINGLE SHEET AND EPSTEIN TEST SPECIMENS

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 62581, which is a technical report, has been prepared by IEC technical committee 68: Magnetic alloys and steels.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
68/411/DTR	68/414/RVC

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

Magnetostriction is one of the magnetic properties that accompany ferromagnetism. It causes reversible deformations of a material body due to magnetization arising from an applied magnetic field.

Nowadays, the environmental problem of acoustic noise pollution caused by transformers and other applications of electrical steels (e.g. ballast, motors, etc.) is a concern of industry [31][1]. Magnetostriction of electrical steels is recognized as one of the causes of the problem and a standardization of methods of measurement of the magnetostriction is required to advance developments in materials to address this problem.

Historically, several methods have been used to measure magnetostriction including strain gauge, capacitance, differential transformer, piezoelectric pick-up and piezoelectric accelerometer methods. However, these methods require skill to set up the sensor accurately and to avoid vibrational noise that accompanies these contact methods. To solve these problems, optical methods that adopt optical vibrometers and optical displacement meters have been developed [1]-[8].

The optical method satisfies the following requirements for the measurement: non-contact, high resolution, high reproducibility and ease of operation without any special skill on the part of the operator. Several optical sensors can be used: laser Doppler vibrometers, heterodyne displacement meters and laser displacement meters with high resolution.

Magnetostriction is a magneto-mechanical phenomenon which accompanies the change of the volume fraction of magnetic domains which have a certain magnetic orientation with respect to the direction of the applied magnetic field, and which is intrinsically sensitive to stress [14],[15]. The stress sensitivity is dependent on material conditions such as grain orientation, residual stress and coating tension. The magnetostriction of electrical steel is increased by compressive stresses in the magnetizing direction rather than tensile stresses [9],[16]-[23]. Magnetic cores of electrical machines such as transformers often contain areas of increased stress. Therefore the stress sensitivity should be evaluated under a specified stress.

The acoustic noise emission from transformers and other machines is usually evaluated in terms of the A-weighted sound pressure level specified in IEC 61672-1. Vibration velocities caused by magnetostriction are transformed into sound pressure on the surface of the materials. Therefore, A-weighted characteristics of magnetostriction, such as A-weighted magnetostriction velocity level or A-weighted magnetostriction acceleration level, are necessary for the assessment of electrical steel sheets with respect to the acoustic noise [24]-[26].

This technical report is comprised of articles which review the optical and accelerometer methods of measurement of magnetostriction with the aim of producing a standard method of measurement of magnetostriction.

Two methods, by a single sheet tester and by a single strip tester, are described. The former should be applied to single sheet specimens with width of not less than 100 mm which have not been stress relief annealed. The latter method should be applied to Epstein test specimens, which may have been stress relief annealed to remove stresses imparted to the specimens during preparation.

---

[1] The figures in square brackets refer to the Bibliography.

ELECTRICAL STEEL – METHODS OF MEASUREMENT OF THE MAGNETOSTRICTION CHARACTERISTICS BY MEANS OF SINGLE SHEET AND EPSTEIN TEST SPECIMENS

1 Scope

This technical report describes the general principles and technical details of the measurement of the magnetostriction of single sheet specimens preferably 500 mm long and 100 mm wide and Epstein strip specimens, specified in IEC 60404-2, of electrical steel by means of optical sensors and accelerometers.

These methods are applicable to test specimens obtained from electrical steel sheets and strips of any grade. The characteristics of magnetostriction are determined for a sinusoidal induced voltage, for specified peak values of magnetic polarization and for a specified frequency.

The measurements are made at an ambient temperature of 23 °C ± 5 °C on test specimens which have first been demagnetized.

2 Normative references

The following referenced documents are indispensable for the application 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 60050-121, *International Electrotechnical Vocabulary – Part 121: Electromagnetism*

IEC 60050-221, *International Electrotechnical Vocabulary – Chapter 221: Magnetic materials and components*

IEC 60404-2, *Magnetic materials – Part 2: Methods of measurement of the magnetic properties of electrical steel sheet and strip by means of an Epstein frame*

IEC 60404-3:1992, *Magnetic materials – Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester*
Amendment 1 (2002)
Amendment 2 (2009)

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