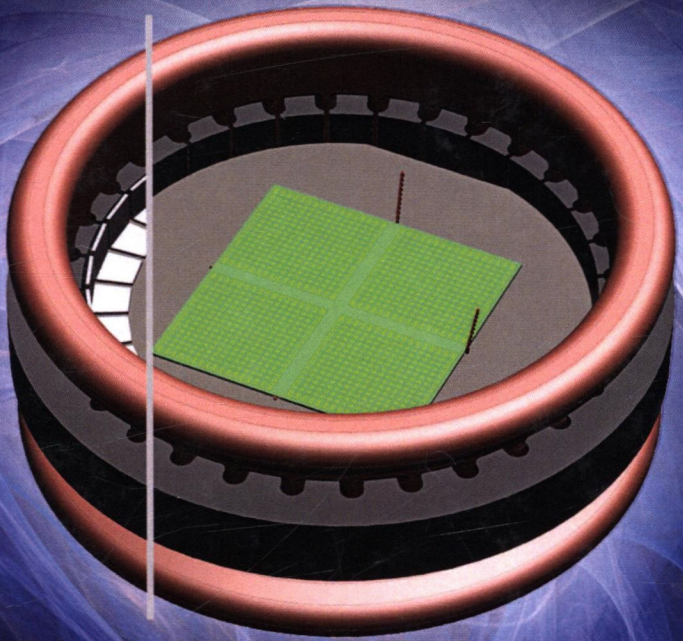
Characterisation of Soft Magnetic Materials Under Rotational Magnetisation



Stanislaw Zurek

CRC Press
Taylor & Francis Group

Electrical Engineering

The book presents practical aspects related to the measurement of rotational power loss in soft magnetic materials. The book furthermore focuses on practical aspects of performing such measurements, the associated difficulties as well as solutions to the most common problems. Numerous practical aspects, hands-on experience, and most commonly encountered pitfalls are heavily discussed in the book. The text begins with introduction to magnetism, then follows with definitions of measurement methods of rotational power loss from physical viewpoint. Two chapters describe and detail the various sensors which can be employed for such measurements as well as all the aspects of designing, making, and using a magnetising apparatus. A synthesis of the likely optimal design of a magnetising apparatus is also given, preceded with the full reasoning based on all the research carried out to date. **Characterisation of Soft Magnetic Materials Under Rotational Magnetisation** serves as an excellent starting point for any student having to perform magnetic measurements under rotational magnetisation, but also under 1D, 2D or 3D excitation. Because the methods, sensors, and apparatus are extensively discussed it will also be a great reference for more senior researchers and experts in the field. There is a whole chapter devoted to analysis of measurement uncertainty. This subject is rarely published for magnetic measurements, which makes it more difficult for all researchers to understand the concepts and methodology used in uncertainty estimation. This chapter not only introduces the whole subject, but also provides multiple step-by-step examples which can be easily followed, from very simple cases to much more complex ones. All equations are presented with full SI units which greatly helps in practical application of the presented methodology. Each chapter is written in such a way that it can be studied on its own, so that the reader can focus only on the specific aspects, as required.

The most comprehensive book on rotational magnetisation power loss measurements.

- Text compiled at a level accessible to self-learning students, but also containing all information required for reference for experts in the field
- Unique practical comments and know-how throughout the book, from drilling holes, through digital feedback implementation, to precision of calculations
- All equations are presented in an easy-to-use form, with the corresponding physical units as well as with numerous practical comments
- A whole chapter devoted to uncertainty analysis, with easy-to-follow explanation of the basic terms and step-by-step practical examples
- Complete definition of numerical integration for signals and power loss

K35735

CRC Press
Taylor & Francis Group
an informa business

www.crcpress.com

6000 Broken Sound Parkway, NW
Suite 300, Boca Raton, FL 33487
711 Third Avenue
New York, NY 10017
2 Park Square, Milton Park
Abingdon, Oxon OX14 4RN, UK

ISBN-13: 978-1-138-30436-9
90000
9 781138 304369

ZUREK

Characterisation of Soft Magnetic Materials Under Rotational Magnetisation

CRC

Characterisation of Soft Magnetic Materials Under Rotational Magnetisation

Stanislaw Zurek

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

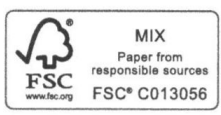
International Standard Book Number-13: 978-1-138-30436-9 (Hardback)

Library of Congress Cataloging-in-Publication Data

Names: Zurek, Stanislaw (Electrical engineer), author.
Title: Characterisation of soft magnetic materials under rotational magnetisation / Stanislaw Zurek.
Description: Boca Raton : Taylor & Francis, CRC Press, 2017. | Includes bibliographical references and index.
Identifiers: LCCN 2017033847| ISBN 9781138304369 (hardback : alk. paper) | ISBN 9780203730126 (ebook)
Subjects: LCSH: Electronics--Materials. | Magnetic materials. | Magnetization. | Plasticity.
Classification: LCC TK7871.15.M3 Z87 2017 | DDC 620.1/1297--dc23
LC record available at https://lccn.loc.gov/2017033847

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com



Printed and bound in Great Britain by
TJ International Ltd, Padstow, Cornwall

Characterisation of Soft Magnetic Materials Under Rotational Magnetisation

This book is dedicated to the most resourceful, the wisest, the most hard-working and the bravest person I ever knew – my mother Janina Żurek who used to say:

We learn our whole life, and we still die stupid.

Symbols, Acronyms and Abbreviations

$\odot$	a circle with a dot represents a vector, whose direction is perpendicular to the surface of the page and the sense is pointing towards the reader
$\otimes$	a circle with a cross represents a vector, whose direction is perpendicular to the surface of the page and the sense is pointing away from the reader
1&2DM	International Workshop on 1&2 Dimensional Magnetic Measurement and Testing
1D	one-dimensional, uni-directional
2D	two-dimensional (including rotational)
2DM	International Workshop on 1&2 Dimensional Magnetic Measurement and Testing
3d	electron shell important for ferromagnetism
3D	three-dimensional
a	interatomic distance (m)
a_{rec}	range of interval in a rectangular distribution (various units)
a_{tri}	range of interval in a triangular distribution (various units)
a.u.	arbitrary units
A	location 'A', or ammeter
A	area (m^2)
A_1, A_2	area (m^2)
A_C	area of a conductive pad (m^2)
A_{coil}	active area of a coil (m^2)
A_i	numerical value of 'partial area' of i-th trapezoid in mathematical integration of digital signal (V · s)
AI+	positive analogue input
AI–	negative analogue input
AI GND	analogue input ground
AI SENSE	analogue input sense, reference for non-referenced single-ended mode input
AISN	*see* AI SENSE
A_{sample}	cross-section area of a sample (m^2)
A_{yoke}	cross-section area of a yoke (m^2)
ADC	analogue-to-digital converter
AVG	average of rectified voltage signal (V)
B	location 'B'
B	flux density (T)
$\bar{B}$	amplitude of purely circular B (T)
$\vec{B}$	flux density vector

B_1	flux density in medium '1'
B_{1n}	normal component of B_1
B_{1t}	tangential component of B_1
B_2	flux density in medium '2'
B_{2n}	normal component of B_2
B_{2t}	tangential component of B_2
B_A	(amplitude of) alternating flux density (T)
B_C	(modulus of vector of) circular flux density (T)
B_{mean}	flux density averaged over an area (T)
BN	Barkhausen noise
B_p	peak flux density (T)
B_{peak}	peak flux density (T)
B_r	remanence (T)
B_R	rotational flux density (T)
B_{sample}	flux density in a sample (T)
B_{yoke}	flux density in a yoke (T)
B_x	x component of B (T)
B_y	y component of B (T)
B_z	z component of B (T)
c	specific heat (J/(kg · K))
C	capacitance (F)
C_0	constant value in a given equation (various units)
C_1	constant value in a given equation (various units)
C_2	constant value in a given equation (various units)
C_a	material constant in additional component of power loss (J · $\sqrt{s}$/kg)
C_e	material constant in eddy current component of power loss (J · s/kg)
C_h	material constant in hysteresis component of power loss (J/kg)
$C_{integral}$	constant value resulting from integration of any function (various units)
C_n	constant value in a given equation (various units)
CNC	computer numerical control
C_x	constant value in a given equation (various units)
CGO	conventional grain-oriented electrical steel
d	thickness (m)
d_f	degrees of freedom (unitless)
${}_e d_f$	effective degrees of freedom (unitless)
d_r	digit of resolution (various units)
D	specific density (kg/m^3)
DAC	digital-to-analogue converter
DAQ	data acquisition device
DGO	double grain-oriented electrical steel
DMM	digital multimeter
E	energy in (J), (J/kg) or (J/m^3)
E_{circle}	energy in circular motion (J)
E_{line}	energy in linear motion (J)
E	electric field (V/m)

$\vec{E}$	electric field vector
EDM	electrical discharge machining
EMF	electromotive force (V)
ENOB	effective number of bits
E_x	x component of electric field (V/m)
E_y	y component of electric field (V/m)
E_Y	Young's modulus of elasticity (Pa)
E_z	z component of electric field (V/m)
f	frequency (Hz)
F	mechanical force (N)
FEM	finite-element method
FF	form factor (unitless)
FFF	flux fringing factor (unitless)
FSO	full-scale output
g	gravity (m/s^2)
g_a	acceleration (m/s^2)
G	gain (unitless)
G_{corr}	correction gain (unitless)
G_{DF}	digital feedback gain (unitless)
G_{sys}	system gain (unitless)
GF	gauge factor (unitless)
h	generic function (various units)
h_0, h_1, h_2, h_i, h_n	amplitudes of harmonics (various units)
H	magnetic field strength (A/m)
$\vec{H}$	magnetic field vector
H_1	magnetic field strength in medium '1'
H_{1n}	normal component of H_1
H_{1t}	tangential component of H_1
H_2	magnetic field strength in medium '2'
H_{2n}	normal component of H_2
H_{2t}	tangential component of H_2
H_a	applied magnetic field (A/m)
H_c	coercivity (A/m)
${}_BH_c$	coercivity value derived from a B–H loop (A/m)
${}_JH_c$	coercivity value derived from a J–H loop (A/m)
H_d	demagnetising magnetic field (A/m)
H_{mean}	magnetic field strength averaged over an area (A/m)
HGO	high-permeability grain-oriented electrical steel
H_p	peak magnetic field strength (A/m)
H_x	x component of H (A/m)
H_y	y component of H (A/m)
H_z	z component of H (A/m)
i	subsequent item in a set, series or array
I	electric current (A)
I_1	primary current (A)

I_2	secondary current (A)
I_e	eddy current (A)
I_p	peak current (A)
I_x	current for the x channel (A)
I_y	current for the y channel (A)
IM	intermodulation
IMD	intermodulation
j	subsequent item in a set, series or array
J	magnetic polarisation (T)
$J_\parallel$	parallel polarisation (T)
$J_\perp$	perpendicular polarisation (T)
J_p	peak polarisation (T)
J_{sat}	saturation polarisation (T)
k	coefficient of mechanical friction (unitless)
k_Q	coverage factor (unitless)
$k_{Q,t}$	Student's distribution correction factor (unitless)
K	Poynting–Umov vector (W)
K_0	magnetocrystalline anisotropy constant (J/m^3)
K_1	magnetocrystalline anisotropy constant (J/m^3)
K_2	magnetocrystalline anisotropy constant (J/m^3)
K_t	heat transfer coefficient (W/(kg · K))
l	length or distance (m)
l_1	length or distance (m)
l_2	length or distance (m)
l_{coil}	length or path of the coil (m)
l_{gap}	length of air gap (m)
l_{lag}	lagging distance in circular motion (m)
$l_{surface}$	length or path on the surface of the sample (m)
l_{yoke}	length of yoke (m)
L	inductance (H)
m	mass (kg)
M	magnetisation (A/m)
MAE	magneto-acoustic emissions
MMF	magnetomotive force (A)
MOKE	magneto-optic Kerr effect
M_S	magnetisation saturation (A/m)
n	number of items, e.g. turns or points (unitless)
N	number of items, e.g. turns or points (unitless)
N_1	primary turns (unitless)
N_2	secondary turns (unitless)
N_{BN}	number of elements (values) in the digitised Barkhausen noise
N_d	demagnetising coefficient (unitless)
NO	non-oriented electrical steel
nom	nominal value (various units)
NTC	negative temperature coefficient
opamp	operational amplifier

p	instantaneous power loss (W)
P	power in (W), (W/kg) or (W/m^3)
P_a	additional component of power loss, in (W), (W/kg) or (W/m^3)
P_{circle}	power in circular motion (W)
P_e	eddy current component of power loss, in (W), (W/kg) or (W/m^3)
P_h	hysteresis component of power loss, in (W), (W/kg) or (W/m^3)
P_h	hysteresis component of power loss, in (W), (W/kg) or (W/m^3)
PA	partial area (various units)
PID	proportional–integral–derivative (controller)
P_{rot}	rotational power loss, in (W), (W/kg) or (W/m^3)
P_x	component in calculation of rotational power loss, in (W), (W/kg) or (W/m^3)
P_y	component in calculation of rotational power loss, in (W), (W/kg) or (W/m^3)
PLC	power line cycles (unitless)
PS	power spectrum of Barkhausen noise signal
PTC	positive temperature coefficient
Q	probability (unitless)
Q_t	probability in Student's t-distribution (unitless)
r	radius (m)
R	resistance (Ω)
R_0	additional resistance (Ω)
R_1, R_2	resistance values (Ω)
R_{in}	input resistance (Ω)
R_m	measured resistance (Ω)
R_{ref}	reference resistance (Ω)
R_s	resistance of a shunt resistor (Ω)
RS− and RS+	remote sensing connections for a half-bridge circuit
RCP	Rogowski–Chattock potentiometer
RMS	root mean square
s	system gain, equivalent to G_{sys} (unitless)
S	sensitivity or sensitivity coefficient (various units)
$\boldsymbol{S}_{control}$	controlled signal (various units)
$\boldsymbol{S}_{corr}$	correction signal (various units)
$\boldsymbol{S}_{diff}$	difference signal (various units)
$\boldsymbol{S}_{gen}$	generated signal (various units)
$\boldsymbol{S}_H$	signal from sensor of H (various units)
$\boldsymbol{S}_{target}$	target signal (various units)
SC− and SC+	shunt calibration connections for a half-bridge circuit
SI	International System of units (*Le Système International d'unités*)
t	time (s)
t_D	delay time (s)
t_L	triggering correction time (s)
t_{on}	time instant of a start of a process (s)
t_{off}	time instant of an end of a process (s)
t_S	sampling time interval (s)

T	length of cycle or period (s)
T_0	starting temperature (K)
THD	total harmonic distortion (%)
T_m	measured temperature (K)
T_{ref}	reference temperature (K)
TNP	total number of peaks of Barkhausen noise signal (unitless)
TSA	total sum of amplitudes of Barkhausen noise signal (V)
TX	transformer
u	uncertainty (various units)
u_c	combined uncertainty (various units)
${}_e u_c$	expanded combined uncertainty (various units)
u_s	standard uncertainty (various units)
$u_{s,S}$	scaled standard uncertainty (various units)
v	variable (various units)
$\underline{v}$	average of a variable v (various units)
v_{-1}, v_0, v_1, etc.	subsequent values (various units)
v_i	ith value (various units)
v'_{-1}, v'_0, v'_1, etc.	subsequent approximated values (various units)
v_E	expected value (V)
v_L	triggering level (V)
v_n	nth value (various units)
v_{nom}	nominal value (various units)
v_R	real or actual value (V)
$v(t)$	approximating function (V)
V	voltage (V)
V	voltmeter
V_0	voltage (V)
V_1	voltage (V)
V_2	voltage (V)
V_3	voltage (V)
V_a	voltage at a point 'a' (V)
V_A	voltage in part 'A' (V)
V_{avg}	average voltage (V)
V_{AVG}	average voltage (V)
V_b	voltage at a point 'b' (V)
V_B	voltage in part 'B' (V)
$V_{B\text{-}coil}$	B-coil voltage (V)
V_{BN}	output voltage of a Barkhausen noise sensor (V)
V_H	output voltage of a Hall-effect sensor (V)
V_i	ith numerical voltage value (V)
V_{in}	input voltage (V)
$V_{indirect}$	voltage induced in an indirect coil (V)
V_m	measurand (various units)
V_M	magnetic potential (A/m)
$V_{M(A,B)}$	magnetic potential difference between points 'A' and 'B' (A/m)
V_{max}	maximum voltage (V)

$\|V\|_{mean}$	mean value of rectified voltage (V)
V_{min}	minimum voltage (V)
V_{NP}	needle probe sensor voltage (V)
V_{out}	output voltage (V)
$V_{pk\text{-}pk}$	voltage peak-to-peak (V)
V_r	voltage across a shunt resistor (V)
V_{ref}	reference voltage (V)
V_{res}	voltage resolution (V)
V_{RMS}	RMS value of voltage (V)
V_s	sample volume (m^3)
V_{shunt}	voltage across shunt resistor (V)
V_{supply}	supply voltage (V)
V_{th}	thermal noise voltage (V)
V_x	voltage for the x channel (V)
V_y	voltage for the y channel (V)
W	wattmeter
W_R	rotational loss (W)
WCM	Wolfson Centre for Magnetics, Cardiff University, Cardiff, UK
x	direction in orthogonal system of coordinates
x'	apparent direction, deviated from x
y	direction in orthogonal system of coordinates
y'	apparent direction, deviated from y
z	direction in orthogonal system of coordinates
$\vec{x}$	unit vector in direction x
$\vec{y}$	unit vector in direction y
$\vec{z}$	unit vector in direction z

GREEK CHARACTERS

α	arbitrary direction of magnetostriction (rad)
α *iron*	ferromagnetic form of iron
α_k	angle of rotation of polarised light beam in the longitudinal Kerr effect (rad)
γ	electric conductivity (S/m)
γ *iron*	non-ferromagnetic form of iron
Γ	function described by Equation 5.9
Δ	change or difference of any parameter
Δl	change of length (m)
Δt	change of time (s)
δ	error of angular positioning (rad)
θ	angle of rotation (rad)
θ_x	angle of rotation of apparent axis x' (rad)
θ_y	angle of rotation of apparent axis y' (rad)
ϑ	angle of incident beam in Kerr microscopy (rad)
λ	magnetostriction (m/m or unitless)
$\lambda_{pk\text{-}pk}$	peak-to-peak magnetostriction (m/m or unitless)

μ	magnetic permeability, $\mu = \mu_r \cdot \mu_0$ (H/m)
μ_0	magnetic constant, magnetic permeability of free space $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ (H/m)
μ_1	magnetic permeability of medium '1'
μ_2	magnetic permeability of medium '2'
μ_r	relative magnetic permeability $\mu_r = \mu/\mu_0$ (unitless)
ρ	correlation coefficient (unitless)
ς	tangential stress (Pa)
σ	stress (Pa)
σ_s	standard deviation (various units)
${}_v\sigma_s^2$	variance (various units)
$\sigma_{s,rec}$	standard deviation in rectangular distribution (various units)
$\sigma_{s,tri}$	standard deviation in triangular distribution (various units)
σ_{sdom}	standard deviation of the mean (various units)
τ	torque (N · m)
ϕ	phase angle or angular lag (rad)
ω	angular frequency (rad/s)
Φ	magnetic flux (Wb)
Φ_{coil}	magnetic flux in a coil (Wb)
Φ_{sample}	magnetic flux in a sample (Wb)
Φ_{yoke}	magnetic flux in a yoke (Wb)
χ	magnetic susceptibility, $\chi = \mu_r - 1$ (unitless)