Vibration Monitoring of Induction Motors

Master the art of vibration monitoring of induction motors with this unique guide to on-line condition assessment and fault diagnosis, building on the author's 50 years of investigative expertise.
It includes:

- Robust techniques for diagnosis of a wide range of common faults, including shaft misalignment and/or soft foot, rolling element bearing faults, sleeve bearing faults, magnetic and vibrational issues, resonance in vertical motor drives and vibration and acoustic noise from inverters.
- Detailed technical coverage of 30 real-world industrial case studies, from initial vibration spectrum analysis through to fault diagnosis and final strip-down.
- An introduction to real-world vibration spectrum analysis for fault diagnosis, and practical guidelines to reduce bearing failure through effective grease management.

This definitive book is essential reading for industrial end users, engineers and technicians working in motor design, manufacturing and condition monitoring. It will also be of interest to researchers and graduate students working on condition monitoring.

William T. Thomson is the Director of EM Diagnostics Ltd, and a former Professor of Electrical Machines at Robert Gordon University. He has over 50 years of experience in condition monitoring of induction motor drives, and is a Senior Member of the IEEE, a Chartered Engineer and a Fellow of the IET.

Vibration Monitoring of Induction Motors

Practical Diagnosis of Faults via Industrial Case Studies

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Preface

Vibration condition monitoring has been used for many years to diagnose mechanical faults in bearings, gearboxes, compressors and pumps. Numerous text books cover these topics but none focus on vibration monitoring to diagnose faults in induction motors.

This book is unique because it is solely dedicated to vibration monitoring and analysis to diagnose faults in induction motors.

There are 30 industrial case histories which include both theoretical and practical knowledge for on-line condition assessment of induction motors. A key feature of these case histories is closure of the loop between the diagnosis of faults using vibration spectrum analysis and subsequent strip-down of the motors and accompanying photographic evidence of, for example, faulty bearings. The industrial case histories include:

Five on the diagnosis of shaft misalignment and/or soft foot.
Fifteen on the diagnosis of rolling element bearing faults.
Three on vibration problems in sleeve bearings.
Four on problems due to magnetic forces and vibration.
Three on miscellaneous problems including resonance in a vertical induction motor drive, vibration and acoustic noise from induction motors supplied from inverters.

The case histories are presented in detail because a broad-brush, superficial presentation that lacks clarity and evidence as to how the fault was diagnosed is meaningless to the reader. Each case history is stand-alone and does not require the reader to scroll backwards or forwards within the book to understand the vibration measurements, spectrum analysis and predictions.

Chapter 1 provides an overview of publications on sources of vibration in electrical machines. Problems in rolling element bearings account for the largest number of failures of induction motors, therefore a review is presented on the use of vibration measurements and spectrum analysis to diagnose faults in rolling element bearings. The practical difficulty of accessing the housings of rolling element bearings is strongly emphasised, because if bearing housings cannot be accessed then it is more difficult to diagnose bearing faults.

A brief overview of shaft misalignment and soft foot in induction motor drives is included and five industrial case histories are presented on vibration analysis to detect shaft misalignment and/or soft foot.

Chapter 2 is a preparatory chapter for Chapters 3 and 4 and presents the main types and basic features of rolling element bearings that are used in induction motors.

Chapter 3 presents an overview of the types and causes of defects that occur in rolling element bearings to support the case histories in Chapters 4 to 8.

Chapter 4 presents an introduction to vibration spectrum analysis to diagnose faults in rolling element bearings in induction motors. This chapter is a precursor to the presentation of industrial case histories in Chapters 5 to 8 using conventional vibration spectrum analysis to diagnose the onset of faults in rolling element bearings before actual bearing failures occur.

It is emphasised that previously published books and papers that cover the theory and application of vibration monitoring to diagnose faults in rolling element bearings assume that vibration transducers such as accelerometers can always be mounted on the bearing housings. In many cases access to bearing housings is not practically possible on induction motors and this is a key fact that is demonstrated in this book.

Chapter 5 presents industrial case histories using VSA to diagnose cage faults in bearings of SCIMs.

Chapter 6 presents industrial case histories using VSA to diagnose inner and outer race faults in bearings of SCIMs.

Chapter 7 presents industrial case histories using VSA to diagnose false brinelling and skidding problems in cylindrical roller bearings in SCIMs.

Chapter 8 presents industrial case histories using VSA to diagnose miscellaneous faults in rolling element bearings in SCIMs.

Chapter 9 presents fundamental knowledge on the construction and operation of sleeve bearings. The practical measurement of shaft displacement is also described, to support the case histories in this chapter on vibration monitoring to diagnose problems in sleeve bearings.

Chapter 10 presents the fundamental causes of electromagnetic forces and consequential vibration in induction motors, including the twice supply frequency component and its harmonics, and the classical rotor slot passing frequency components.

Chapter 11 presents industrial case histories on miscellaneous problems such as mechanical resonance in a vertical induction motor drive and vibration and acoustic noise from induction motors supplied by inverters.

Chapter 12 presents an appraisal on VSA to diagnose faults in rolling element bearings. A discussion is provided on the key outcome that end users hope to achieve from vibration monitoring, which is the prognosis of remaining operational life of a SCIM after a fault is diagnosed.

It is also reiterated, via more photographic evidence, that access to mount temporary accelerometers directly on the bearing housings of rolling element bearings used in induction motors can be difficult.

Guidelines are given for grease management of rolling element bearings because of the predominance of failures being caused by incorrect greasing practice.

Industrial end users, motor manufacturers, condition monitoring companies and repairers of induction motors are the target market for this book. It is not a classical academic text for undergraduate university or college courses. However, it may well be of interest to post-graduate research students and academic staff with a specific interest in condition monitoring of induction motor drives because the case histories demonstrate what the real challenges are in industry.

This book is not suited to having questions at the end of each chapter and readers can contact the author directly if they have questions on its content.

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About the Author

Bill was born in Scotland in 1946 and started his career in 1961 as a maintenance electrician. He has worked with induction motors at all levels from craft apprentice through to appointment as a professor in electrical machines in 1990. For the past 20 years he has been, and still is, the managing director of his own company providing consulting services in condition monitoring of electrical machines and drives.

Evening class study provided the vocational qualifications to enter the University of Strathclyde (Glasgow, Scotland) in 1970. In 1973 he graduated with an Honours degree in Electrical & Electronic Engineering specialising in electrical machines. From 1973 to 1977 he was a noise and vibration engineer with Hoover Ltd. In 1977 he was awarded a master's degree from the University of Strathclyde for a research thesis entitled 'Reduction of Acoustic Noise and Vibration from Small-Power Electric Motors'. From 1977 to 1979, Bill was a lecturer in electrical power at the Hong Kong Polytechnic and from 1979 until 2001 he was a lecturer (1979–83), senior lecturer (1983–90) and professor (1990–2001) at Robert Gordon University in Aberdeen, Scotland. In 1980, Bill initiated his research on condition monitoring of induction motors and received research funding from power utilities and major oil companies. The focus of the research was on the industrial application of vibration analysis and Motor Current Signature Analysis (MCSA) to diagnose faults in induction motors and drives before failures occur. Bill successfully supervised ten PhD and eight MPhil students.

He left academia in 2001 to start his own company and is the Director and principal consultant of EM Diagnostics Ltd providing consultancy services on the operation and condition monitoring of induction motors to power stations, petrochemical refineries, natural gas refineries and offshore oil and gas production platforms. He has published 72 papers on condition monitoring of induction motors in engineering journals such as *IEEE Transactions* (USA), *IEE Proceedings* (UK), and at International IEEE and IEE (IET, UK) conferences.

He is the co-author of an IEEE Press Wiley publication in 2017: William T. Thomson and Ian Culbert, *Current Signature Analysis for Condition Monitoring of Cage Induction Motors: Industrial Application and Case Histories.* Bill is a SMIEEE, FIEE (IET) in the UK and a chartered professional engineer registered in the UK. He was awarded the Queen's award for technological achievement in 1992 for knowledge input to 'Motor monitor' marketed by Entek, USA. In 1999, Bill provided access to his knowledge on Motor Current Signature Analysis, via a licence from Robert Gordon University, Scotland, to Iris Power, Canada, for the development of an MCSA instrument.

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Sincere thanks are expressed to Mr Archie Low and Mr Donald Sutherland, formerly of Robert Gordon University (RGU), Scotland, for their indispensable contributions to the design and construction of fault producing, 3-phase induction motor test rigs.

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Mr Alistair Carr is acknowledged for his excellent advice and contributions that he provided to the author to produce Sections 9.1.1 through to 9.1.2.4, which cover an introduction to sleeve bearings in large HV induction motors. Alistair is a senior electrical machines consultant with EM Diagnostics Ltd (author is the Director) and was appointed in November 2014. He was formerly Head of Test with Parsons Peebles, Scotland, and was employed by this company for 42 years.

Mr Bill Lockley, Life Fellow of IEEE, Calgary, Canada, is duly acknowledged for his invaluable and private review of the manuscript, which was by personal invitation from the author.

Bill dedicates this book to his wife, Mary Thomson, for her irreplaceable support, patience and encouragement throughout his career which made the writing of this book become a reality; without Mary, it would not have been possible.

William T. Thomson

Biographies of Personnel in the Acknowledgements

Ellis Hood BSc (Eng) Hons 2.1 MIEE CEng FTC (coms) CGLI

1953–55: Telecommunications Engineering training.
1955–57: National Service in RAF, wireless training, second line maintenance on V Bomber gear.
1957–60: UK Post Office Technical Officer in Training – POED.
1960–66: Post Office Technical Officer, Line Transmission. Passed Post Office Executive Engineers Board (1970).
1970–73: Lecturer in Telecomms and Electrical Engineering, Aberdeen Technical College.
1973–77: Napier University, Edinburgh, Lecturer in Electrical Engineering.
1977–79: Secondary School Teacher of Mathematics – Hilton Academy Aberdeen.
1979–90: Robert Gordon University, Aberdeen. Lecturer (1979–84), Senior Lecturer (1984–90) in Telecomms andElectrical Engineering, Course leader on HND course in Electrical Engineering, 1979–88 and course leader on combined BSc/HND course – the first of its kind in Scotland, 1988–90.

Education

1953: Scottish Higher Leaving Certificate.
1953–55/64–66: Full Technological Certificate in Telecommunications CGLI.
1966–70: BSc Electrical Engineering (Hons 2.1), University of Aberdeen, Scotland.
1971–72: Further Education Teaching Certificate in Engineering and Mathematics 1971–72.
1977: PGSCE Secondary Mathematics Teaching Certificate.
1984: MIERE CEng, MIEE 1987.

Dr G. W. D. M. Gunawardene BSc, MSc, PhD

1973–74: Gresham Lion Electronics, Twickenham, Middlesex, Test Technician.
1974–75: INSPEC, IEE, Hitchin, Hertfordshire, Technical Publications Inspector.
1976–79: Sheffield City Polytechnic, now Sheffield Hallam University, Research Assistant.
1979–2010: Robert Gordon University, Lecturer.

Education

1955–67: Moratu Maha Vidyalaya, Moratuwa, Sri Lanka, Primary and Secondary Education.
1967–69: Katubedda Technical College, Sri Lanka, Technician Course.
1969–73: Kingston Polytechnic, Middlesex, BSc Electrical Engineering.
1975–76: University of Bradford, MSc Control Engineering.
1976–79: Sheffield City Polytechnic, now Sheffield Hallam University, PhD.

Publications

(1) G. W. D. M. Gunawardene and M. J. Grimble, Development of a Static Model for a Sendzimir Cold Rolling Mill, *IMACS Symposium on Control Systems*, Technical University, Vienna, Sept. 1978.
(2) G. W. D. M. Gunawardene, M. J. Grimble and A. Thomson, Static Model for Sendzimir Cold Rolling Mill, *Metals Technology*, July 1981.
(3) Static Model of a Sendzimir Mill for Use in Shape Control, PhD thesis, 1982.
(4) G. W. D. M. Gunawardene and E. Forest, Controllability of Linear Control Systems using Gilbert and Kalman Criteria, *International Journal of Mathematical Education*, Sept. 1996.

Achievements

A programme to calculate the conditions of Sendzimir Cold Rolling Mill when loaded was developed during the research period which was bought by two steel companies in USA and Sweden.

Nomenclature

Quantity	Quantity symbol	Unit	Unit symbol
Acceleration	a	Metres per second squared	m/s^2
Angular frequency	ω	Radians per second	rad/s
Ball diameter in rolling element bearing	BD	Millimetres	mm
Bearing dynamic capacity	C	Newtons	N
Bearing rating life	L_{10}	Hours	hr
Centrifugal force	$C.F.$	Newtons	N
Coil distribution factor	k_d	Number	–
Coil span factor	k_s	Number	–
Contact angle of bearing surface to outer race	β	Degrees	e.g. 40°
Current (r.m.s.)	I	Ampere	A
Decibel	–	–	dB
Displacement	d	Metres or millimetres	m or mm
Electromagnetic force	F_{em}	Newtons	N
Equivalent bearing load	P	Newtons	N
Frequency of mains supply	f_1	Hertz	Hz
Frequency of rotational speed of rotor	f_r	Hertz	Hz
Fundamental rotational frequency of vibration	$1X$	Hertz	Hz
Flux density	B	Tesla	T
Full-load current	$I_{f.l.}$	Amperes	A
Induced voltage in stator winding per phase	E	Volts	V
Line current	I_L	Amperes	A
Line voltage	V_L	Voltage	V
Lubricating viscosity	v_c	Centistokes	cSt
Magnetic flux	Φ	Weber	Wb
Mass	m	Kilograms	kg
Number of turns	N_T	Integer	–
Number of rolling elements	n_e	Integer	–
Pole pairs	p	Integer	–
Power output	P	Kilowatts or horsepower	kW or H.P.
Power input to the induction motor	P_{in}	Kilowatts	kW

(*cont.*)

Quantity	Quantity symbol	Unit	Unit symbol
Power factor	*p.f.*	Number	–
Pitch diameter of rolling element bearing	*PD*	Millimetres	mm
Rotor slotting vibration frequency component	f_{rv}	Hertz	Hz
Rotor speed	N_r	Revolutions per minute	r/min
Relative permeability of free space	μ_0	Henry per metre	H/m
Rotor bars or slots	R	Integer	–
Synchronous speed	N_s	Revolutions per minute	r/min
Slip	s	–	Number or %
Slip at full-load speed	$s_{f.l.}$	–	Number or %
Speed	n	Revolutions per minute	r/min
Time	t	Seconds	s
Torque	T	Newton metre	N·m
Torque – full-load	$T_{f.l.}$	Newton metre	N·m
Torque – starting	T_s	Newton metre	N·m
Turns per phase	N_{ph}	Integer	–
Voltage	V	Volts or kilovolts	V or kV
Volt-amps	VA	Volt-amperes	VA
Velocity	v	Metres per second or millimetres per second	m/s or mm/s

Acronyms and Abbreviations

API	American Petroleum Institute, USA
ASWLP	Auxiliary Sea Water Lift Pump
BD	Ball Diameter
BPFI	Ball Pass Frequency Inner Race
BPFO	Ball Pass Frequency Outer Race
BS	British Standard
BSF	Ball Spin Frequency
CCGT	Combined Cycle Gas Turbine
C.F.	Centrifugal Force
CM	Condition Monitoring
DE	Drive End
DEA	Drive End Axial
DEH	Drive End Horizontal
DEV	Drive End Vertical
FAT	Factory Acceptance Test
FFT	Fast Fourier Transform
FLC	Full Load Current
FLT	Full Load Torque
FPSO	Floating Production and Oil Off-loading ship
FTF	Fundamental Train Frequency
GRF	Gas Recirculating Fan
HV	High Voltage
H.P.	Horse Power
ISO	International Standards Organization
LNG	Liquid Natural Gas
LV	Low Voltage
MCSA	Motor Current Signature Analysis
NDE	Non Drive End
NDEA	Non Drive End Axial
NDEH	Non Drive End Horizontal
NDEV	Non Drive End Vertical
NEMA	National Electrical Machines Association, USA
OEM	Original Equipment Manufacturer
OIM	Offshore Installation Manager

PD	Pitch Diameter
PM	Planned Maintenance
QA	Quality Assurance
QC	Quality Control
r.m.s. (or R.M.S.)	Root Mean Square
R&D	Research and Development
RCFA	Root Cause Failure Analysis
RTD	Resistance Temperature Detector
SCIM	Squirrel Cage Induction Motor
SPM	Shock Pulse Measurement or Method
SRIM	Slip Ring Induction Motor
SRP	Sulphate Removal Pump
SWIP	Sea Water Injection Pump
TEFC	Totally Enclosed Fan Cooled
VSA	Vibration Spectrum Analysis

Relevant Units of Equivalence Useful for this Book

Metric/SI units	Imperial
1.0 m	39.4 inches
25.4 mm	1.0 inch
1.0 mm	0.0394 inches/39.4 mils (≅40 thou/mils)
50 µm	2.0 thou/mils
25 mm/s	1.0 inch/s
1.0 mm/s	≅0.04 inches/s
1.0 kg	2.2046 lbs (≅2.2 lbs)
1.0 N	0.2248 lbsf (≅0.225 lbsf)
1.0 Nm	0.73756 lbsf-ft (≅0.738 lbsf-ft)
1.0 kg-m^2	0.042 lbs-ft^2
1.0 N/m^2	145×10^{-6} lbsf/$inch^2$
745.7 W (≅746 W)	1.0 H.P.