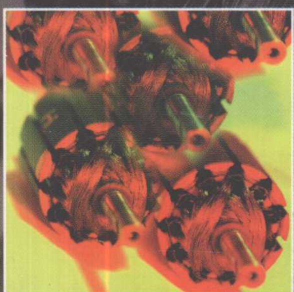
HANDBOOKS

McGraw-Hill

HANDBOOK OF SMALL ELECTRIC MOTORS



WILLIAM H. YEADON, P.E.
ALAN W. YEADON, P.E.

HANDBOOK OF SMALL ELECTRIC MOTORS

William H. Yeadon, P.E. Editor in Chief

Alan W. Yeadon, P.E. Associate Editor

Yeadon Energy Systems, Inc

Yeadon Engineering Services, P.C.

McGraw-Hill

New York Chicago San Francisco Lisbon London
Madrid Mexico City Milan New Delhi
San Juan Seoul Singapore
Sydney Toronto

Library of Congress Cataloging-in-Publication Data

Handbook of small electric motors / William H. Yeadon,
editor in chief, Alan W. Yeadon, associate editor.
p. cm.
ISBN 0-07-072332-X
1. Electric motors, Fractional horsepower. I. Yeadon,
William H. II. Yeadon, Alan W.

TK2537 .H34 2001
621.46—dc21 00-048974

McGraw-Hill

A Division of The ***McGraw-Hill*** *Companies*

1 2 3 4 5 6 7 8 9 0 DOC/DOC 0 7 6 5 4 3 2 1

ISBN 0-07-072332-X

The sponsoring editor for this book was Scott Grillo and the production supervisor was Sherri Souffrance. It was set in Times Roman by North Market Street Graphics.

Printed and bound by R. R. Donnelley & Sons Company.

McGraw-Hill books are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. For more information, please write to the Director of Special Sales, Professional Publishing, McGraw-Hill, Two Penn Plaza, New York, NY 10121-2298. Or contact your local bookstore.

This handbook is intended to be used as a reference for information regarding the design and manufacture of electric motors. It is not intended to encourage or discourage any motor type, design, or process. Some of the configurations or processes described herein may be patented. It is the responsibility of the user of this information to determine if any infringement may occur as a result thereof.

HANDBOOK OF SMALL ELECTRIC MOTORS

This handbook is dedicated to my wife, Luci Yeadon, who took most of the photographs for it.

William H. Yeadon
Editor in Chief

CONTRIBUTORS

Larry C. Anderson *American Hoffman Corporation* (Sec. 3.14)

John S. Bank *Phoenix Electric Manufacturing Company* (Sec. 3.15)

Warren C. Brown *Link Engineering Company* (Sec. 3.10.6)

Joseph H. Bularzik *Magnetics International, Inc.* (Sec. 2.5)

Peter Caine *Oven Systems, Inc.* (Sec. 3.16)

David Carpenter *Vector Fields, Ltd.* (contributed the finite-element plots in Chap. 4)

John Cocco *Loctite Corporation* (Sec. 3.17)

Philip Dolan *Oberg Industries* (Sec. 3.10.5)

Birch L. DeVault *Cutler-Hammer* (Sec. 10.6)

Brad Frustaglio *Yeadon Energy Systems, Inc.* (Sec. 6.4)

Francis Hanejko *Hoeganaes Corporation* (Sec. 2.6)

Duane C. Hanselman *University of Maine* (Secs. 5.1.4 and 10.11)

Daniel P. Heckenkamp *Cutler-Hammer* (Sec. 10.6)

Leon Jackson *LDJ Electronics* (Sec. 3.19)

Dan Jones *Incremotion Associates* (Secs. 5.1.3, 10.12, and 10.13)

Douglas W. Jones *University of Iowa* (Secs. 5.2.10 and 10.8 to 10.10)

Mark A. Juds *Eaton Corporation* (Secs. 1.1 to 1.12)

Robert R. Judd *Judd Consulting Associates* (Secs. 2.2 and 2.3)

Ramani Kalpathi *Dana Corporation* (Sec. 10.7)

John Kauffman *Phelps Dodge Magnet Wire Company* (Sec. 2.10)

Todd L. King *Eaton Corporation* (Sec. 10.6)

H. R. Kokal *Magnetics International, Inc.* (Sec. 2.5)

Robert F. Krause *Magnetics International, Inc.* (Sec. 2.5)

Barry Landers *Electro-Craft Motion Control* (Chap. 9)

Roger O. LaValley *Magnetic Instrumentation, Inc.* (Sec. 3.18)

Bill Lawrence *Oven Systems, Inc.* (Sec. 3.16)

Andrew E. Miller *Software and motor designer* (Secs. 4.5, 6.4.3, and 6.4.4)

Stanley D. Payne *Windamatics Systems, Inc.* (Sec. 3.10.4)

Derrick Peterman *LDJ Electronics* (Sec. 3.19)

Curtis Rebizant *Integrated Engineering Software* (contributed the boundary element plots in Figs. 5.58 to 5.61)

Earl F. Richards *University of Missouri* (Secs. 1.14, 4.1, 6.2, 6.3, and 8.4 to 8.8)

Robert M. Setbacken *Renco Encoders, Inc.* (Secs. 10.1 to 10.5)

Karl H. Schultz *Schultz Associates* (Secs. 3.1 to 3.9)

Joseph J. Stupak Jr. *Oersted Technology Corporation* (Sec. 2.8)

Chris A. Swenski *Yeadon Energy Systems, Inc.* (Secs. 3.6.5, 6.4, and 7.4)

Harry J. Walters *Oberg Industries* (Sec. 3.10.5)

Alan W. Yeadon *Yeadon Engineering Services, PC* (Secs. 3.10, 3.11, and 4.2 to 4.5)

Luci Yeadon *Luci's Photography* (contributed most of the photographs in this handbook)

William H. Yeadon *Yeadon Engineering Services, PC* (Secs. 1.13, 2.1, 2.9, 2.11, 3.10 to 3.12, 4.3, 4.6 to 4.8, 5.1 to 5.3, 6.1, 6.4, 7.1 to 7.4, and 8.1 to 8.3)

PREFACE

When I was first approached about writing this handbook, it seemed like a fairly straightforward task. There was information available from a variety of sources. There were many capable people in the field who could contribute, and there was historical data from many sources.

The intent of this book is to cover the operating theory, practical design approaches, and manufacturing methods for the most common motors now in use. We have tried to meet this intent by including as much information as possible. The universe of motor information is huge, although most of the information is old. It became apparent that much information would have to be left out. We tried to include the basics along with that information we felt was most necessary and useful to those designing, manufacturing, and using motors. This is not a design course or a highly theoretical text but a place where people can go to get practical answers.

We are setting up a section at our Web site, www.yeadoninc.com, for people to comment about the book and tell us of improvements we can make and things they would like to have added to the next edition.

ACKNOWLEDGMENTS

Over the course of my career I have had the privilege to meet many of the giants of this industry. Many I have met through my association with the Small Motors and Motion Association (SMMA) and others through business relationships. Included among them are Dr. Cyril G. Veinott, Professor Philip H. Trickey, Dr. Ben Kuo, Dr. Duane Hanselman, and those authors who have contributed to this handbook.

There is, however, one person of whom I must make special mention. He is Dr. Earl Richards, Professor Emeritus of the University of Missouri at Rolla. This man never ceases to amaze me. He is always willing to help out selflessly with projects of this type. I have taught many motor design courses with him. When a student asks questions of him, he can start at the lowest level of understanding necessary and develop in a very understandable way a logical and reasonable answer to the question. His ability to communicate and teach is truly amazing. He has been very helpful in the preparation of this book.

I also need to acknowledge the dedication of my secretary, Kristina Wodzinski. Without her tireless effort this work would not have been completed.

CONTENTS

CHAPTER 1
BASIC MAGNETICS

Chapter Contributors

Mark A. Juds
Earl F. Richards
William H. Yeadon

Electric motors convert electrical energy into mechanical energy by utilizing the properties of electromagnetic energy conversion. The different types of motors operate in different ways and have different methods of calculating the performance, but all utilize some arrangement of magnetic fields. Understanding the concepts of electromagnetics and the systems of units that are employed is essential to understanding electric motor operation. The first part of this chapter covers the concepts and units and shows how forces are developed. Nonlinearity of magnetic materials and uses of magnetic materials are explained. Energy and coenergy concepts are used to explain forces, motion, and activation. Finally, this chapter explains how motor torque is developed using these concepts.

1.1 UNITS*

Although the rationalized mks system of units [Système International (SI) units] is used in this discussion, there are also at least four other systems of units—cgs, esu, emu, and gaussian] that are used when describing electromagnetic phenomena. These systems are briefly described as follows.

MKS. Meter, kilogram, second.

CGS. Centimeter, gram, second.

* Sections 1.1 to 1.12 contributed by Mark A. Juds, Eaton Corporation.

ESU. CGS with $e_0 = 1$, based on Coulomb's law for electric poles.

EMU. CGS with $\mu_0 = 1$, based on Coulomb's law for magnetic poles.

Gaussian. CGS with electric quantities in esu and magnetic quantities in emu. The factor 4π appears in Maxwell's equation.

Rationalized mks. $\mu_0 = 4\pi \times 10^{-7}$ H/m, based on the force between two wires.

Rationalized cgs. $\mu_0 = 1$, based on Coulomb's law for magnetic poles. The factor 4π appears in Coulomb's law.

The rationalized mks and the rationalized cgs systems of units are the most widely used. These systems are defined in more detail in the following subsections.

1.1.1 The MKS System of Units

The rationalized mks system of units (also called SI units) uses the magnetic units tesla (T) and amps per meter (A/m), for flux density B and magnetizing force H, respectively. In this system, the flux density B is defined first (before H is defined), and is based on the force between two current-carrying wires. A distinction is made between B and H in empty (free) space, and the treatment of magnetization is based on amperian currents (equivalent surface currents).

Total or normal flux density B, T

$$B = \mu_0 (H + M) \tag{1.1}$$

Intrinsic flux density B_i, T

$$B_i = \mu_0 M \tag{1.2}$$

Permeability of free space μ_0, (T·m)/A

$$\mu_0 = 4\pi \times 10^{-7} \tag{1.3}$$

Magnetization M, A/m

$$M = \frac{B_i}{\mu_0} = \frac{m}{V} \tag{1.4}$$

Magnetic moment M, J/T

$$m = MV = pl \tag{1.5}$$

Magnetic pole strength p, A·m

$$p = \frac{m}{l} \tag{1.6}$$

1.1.2 The CGS System of Units

The rationalized cgs system of units uses the magnetic units of gauss (G) and oersted (Oe) for flux density B and magnetizing force H, respectively. In this system, the magnetizing force, or field intensity, H is defined first (before B is defined), and is based on the force between two magnetic poles. No distinction is made between B and H in empty (free) space, and the treatment of magnetization is based on magnetic poles. The unit *emu* is equivalent to an erg per oersted and is understood to mean the electromagnetic unit of magnetic moment.

Total or normal flux density B, G

$$B = H + 4\pi M \tag{1.7}$$

Intrinsic flux density B_i, G

$$B_i = 4\pi M \tag{1.8}$$

Permeability of free space μ_0, G/Oe

$$\mu_0 = 1 \tag{1.9}$$

Magnetization M, emu/cm³

$$M = \frac{B_i}{4\pi} = \frac{m}{v} \tag{1.10}$$

Magnetic moment m, emu

$$m = MV = pl \tag{1.11}$$

Magnetic pole strength p, emu/cm

$$p = \frac{m}{l} \tag{1.12}$$

The magnetization or magnetic polarization M is sometimes represented by the symbols I or J, and the intrinsic flux density B_i is then represented as $4\pi M$, $4\pi I$, or $4\pi J$.

1.1.3 Unit Conversions

Magnetic Flux ϕ

$1.0\ \text{Wb} = 10^8$ line
$= 10^8$ maxwell
$= 1.0\ \text{V·s}$
$= 1.0\ \text{H·A}$
$= 1.0\ \text{T·m}^2$

Magnetic Flux Density B

$1.0\ \text{T} = 1.0\ \text{Wb/m}^2$
$= 10^8\ \text{line/m}^2$
$= 10^8\ \text{maxwell/m}^2$
$= 10^4$ G
$= 10^9\ \gamma$

$1.0\ G = 1.0\ \text{line/cm}^2$
$= 10^{-4}\ T$
$= 10^5\ \gamma$
$= 6.4516\ \text{line/in}^2$

Magnetomotive or Magnetizing Force *NI*

$1.0\ \text{A·turn} = 0.4\ \pi\ \text{Gb}$
$= 0.4\ \pi\ \text{Oe·cm}$

Magnetic Field Intensity *H*

$1.0\ \text{(A·turn)/m} = 4\pi \times 10^{-3}\ \text{Oe}$
$= 4\pi \times 10^{-3}\ \text{Gb/cm}$
$= 0.0254\ \text{(A·turn)/in}$
$1.0\ \text{Oe} = 79.5775\ \text{(A·turn)/m}$
$= 1.0\ \text{Gb/cm}$
$= 2.02127\ \text{(A·turn)/in}$

Permeability μ

$1.0\ \text{(T·m)/(A·turn)} = 10^7/4\pi\ \text{G/Oe}$
$= 1.0\ \text{Wb/(A·turn·m)}$
$= 1.0\ \text{H/m}$
$= 1.0\ \text{N/(amp·turn)}^2$
$1.0\ \text{G/Oe} = 4\pi \times 10^{-7}\ \text{H/m}$

Inductance *L*

$1.0\ \text{H} = 1.0\ \text{(V·s·turn)/A}$
$= 1.0\ \text{(Wb·turn)/A}$
$= 10^8\ \text{(line·turn)/A}$

Energy *W*

$1.0\ \text{J} = 1.0\ \text{W·s}$
$= 1.0\ \text{V·A·s}$
$= 1.0\ \text{Wb·A·turn}$
$= 1.0\ \text{N·m}$
$= 10^8\ \text{line·A·turn}$
$= 10^7\ \text{erg}$

Energy Density *w*

$1.0\ \text{MG·Oe} = 7.958\ \text{kJ/m}^3$
$= 7958\ \text{(T·A·turn)/m}$
$1.0\ \text{(T·A·turn)/m}^3 = 1.0\ \text{J/m}^3$

Force *F*

$1.0\ \text{N} = 1.0\ \text{J/m}$
$= 0.2248\ \text{lb}$
$1.0\ \text{lb} = 4.448\ \text{N}$

Magnetic Moment *m*

$1.0\ \text{emu} = 1.0\ \text{erg/Oe}$
$= 1.0\ \text{erg/G}$
$= 10.0\ \text{A·cm}^2$
$= 10^{-3}\ \text{A·m}^2$
$= 10^{-3}\ \text{J/T}$
$= 4\pi\ \text{G·cm}^3$
$= 4\pi \times 10^{-10}\ \text{Wb·m}$
$= 10^{-7}\ \text{(N·m)/Oe}$

Magnetic Moment of the Electron Spin $\beta = eh/4\pi m_e$

$1.0\ \text{Bohr magneton} = \beta = 9.274 \times 10^{-24}\ \text{J/T}$
$= \beta = 9.274 \times 10^{-24}\ \text{A·m}^2$
$= \beta = 9.274 \times 10^{-21}\ \text{erg/G}$

Constants

Permeability of free space	$\mu_0 = 1.0\ \text{G/Oe}$
	$\mu_0 = 4\pi \times 10^{-7}\ \text{(T·m)/(A·turn)}$
	$\mu_0 = 4\pi \times 10^{-7}\ \text{H/m}$
Electron charge	$e = 1.602177 \times 10^{-19}\ \text{C}$
Electron mass	$m_e = 9.109390 \times 10^{-31}\ \text{kg}$
Plank's constant	$h = 6.6262 \times 10^{-34}\ \text{J·s}$
Velocity of light	$c = 2.997925 \times 10^{8}\ \text{m/s}$
Pi	$\pi = 3.1415926536$
Acceleration of gravity	$g = 9.807\ \text{m/s}^2$
	$= 32.174\ \text{ft/s}^2$
	$= 386.1\ \text{in/s}^2$

Miscellaneous

Length l	$1.0\ \text{m} = 39.37\ \text{in}$
	$= 1.094\ \text{yd}$
	$1.0\ \text{in} = 25.4\ \text{mm}$
Time t	$1.0\ \text{day} = 24\ \text{h}$
	$1.0\ \text{min} = 60\ \text{s}$
Velocity v	$1.0\ \text{m/s} = 3.6\ \text{km/h}$