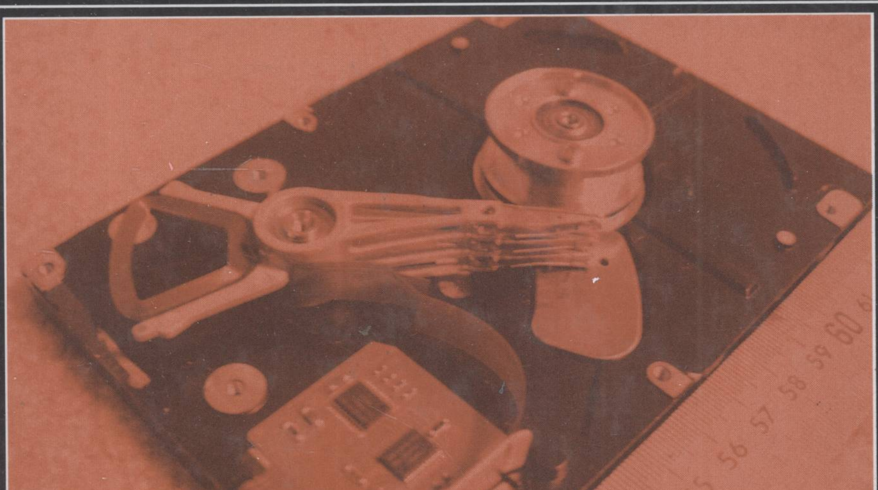
Magnetic Actuators and Sensors



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Preface

This book is written for practicing engineers and engineering students involved with the design or application of magnetic actuators and sensors. The reader should have completed at least one basic course in electrical engineering and/or mechanical engineering. This book is suitable for engineering college juniors, seniors, and graduate students.

IEEE societies whose members will be interested in this book include the Magnetics Society, Computer Society, Power Engineering Society, Industry Applications Society, and Control System Society. Readers of the *IEEE/ASME Transactions on Mechatronics,* sponsored by the IEEE Industrial Electronics Society, may also want to read this book. Many SAE (Society of Automotive Engineers) members might also be very interested in this book because the magnetic devices discussed here are commonly used in automobiles and aircraft.

This book is a suitable text for upper-level engineering undergraduates or graduate students in courses with titles such as "Actuators and Sensors" or "Mechatronics." It can also serve as a supplementary text for courses such as "Electromagnetic Fields," "Electromechanical Energy Conversion," or "Feedback Control Systems." It is also appropriate as a reference book for "Senior Projects" in electrical and mechanical engineering. Its basic material has been used in a 16-hour seminar for industry that I have taught many times at Milwaukee School of Engineering. More than twice as many class hours, however, will be required to thoroughly cover the contents of this book.

The chapters on magnetic actuators are intended to replace a venerable book by Herbert C. Roters, *Electromagnetic Devices,* published by John Wiley & Sons in 1941. Over the decades since 1941, many technological revolutions have occurred. Perhaps the most wide-ranging revolution has been the rise of the modern computer. The computer not only uses magnetic actuators and sensors in its disk drives and external interfaces but also enables new ways of analyzing and designing magnetic devices. Hence this book includes the latest computer-aided engineering methods from the most recently published technical papers. The latest software tools are used, especially the electromagnetic finite-element software package Maxwell SV, which is available to students at no charge from Ansoft Corporation, for which I am a part-time consultant. Other software tools used include SPICE, MATLAB, and Simplorer. Simplorer SV, the student version, is also available to students free of charge from Ansoft Corporation. If desired, the reader can work the computational

examples and problems with other available software packages, which should yield similar results. To download Maxwell SV and Simplorer SV along with their example files, please visit the web site for this book:
ftp://ftp.wiley.com/public/sci_tech_med/magnetic_actuators/

This book is divided into four parts, each containing several chapters. Part 1, on *magnetics,* begins with an introductory chapter defining magnetic actuators and sensors and why they are important. The second chapter is a review of basic electromagnetics, needed because magnetic fields are the key to understanding magnetic actuators and sensors. Chapter 3 is on the reluctance method, a way to approximately calculate magnetic fields by hand. Chapter 4 covers the finite-element method, which calculates magnetic fields very accurately via the computer. Magnetic force is a required output of magnetic actuators and is discussed in Chapter 5, and other magnetic performance parameters are the subject of Chapter 6.

Part 2 is on *actuators.* Chapter 7 discusses DC (direct-current) actuators, while Chapter 8 deals with AC (alternating-current) actuators. The last chapter devoted strictly to magnetic actuators is Chapter 9, on their transient operation.

Part 3 of the book is on *sensors.* Chapter 10 describes in detail the Hall effect and magnetoresistance, and applies these principles to sensing position. Chapter 11 covers many other types of magnetic sensors. However, types of sensors involving quantum effects are not included, because quantum theory is beyond the scope of this book.

Part 4 of the book, on *systems,* covers many systems aspects common to both magnetic actuators and sensors. Chapter 12 presents coil design and temperature calculations. Electromagnetic compatibility issues common to sensors and actuators are discussed in Chapter 13. Electromechanical performance is analyzed in Chapter 14 using coupled finite elements, while Chapter 15 uses electromechanical systems software. Finally, Chapter 16 shows the advantages of electrohydraulic systems that incorporate magnetic actuators and/or sensors.

Many examples are presented throughout the book because my teaching experience has shown that they are vital to learning. The examples that are numbered are simple enough to be fully described, solved, and repeated by the reader. In addition, problems at the ends of the chapters enable the reader to progress beyond the solved examples.

I would like to thank the many engineers whom I have known for making this book possible. Starting with my father, Robert C. Brauer, P.E., it has been my great pleasure to work with you for many decades. I thank my wife, Susan McCord Brauer, for her encouragement and advice on writing. Thanks also go to the reviewers of this book for their many excellent suggestions. All of you have taught me many things. This book is my attempt to summarize some of what I've learned and to pass it on.

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Contents

PART I

MAGNETICS

CHAPTER 1

Introduction

Magnetic actuators and sensors use magnetic fields to produce and sense motion. Magnetic actuators allow an electrical signal to move small or large objects. To obtain an electrical signal that senses the motion, magnetic sensors are often used.

Since computers have inputs and outputs that are electrical signals, magnetic actuators and sensors are ideal for computer control of motion. Hence magnetic actuators and sensors are increasing in popularity. Motion control that was in the past accomplished by manual command is now increasingly carried out by computers with magnetic sensors as their input interface and magnetic actuators as their output interface.

Both magnetic actuators and magnetic sensors are energy conversion devices. Both involve the energy stored in static, transient, or low-frequency magnetic fields. Devices that use electric fields or high-frequency electromagnetic fields are not considered to be magnetic devices and thus are not discussed in this book.

1.1 OVERVIEW OF MAGNETIC ACTUATORS

Figure 1.1 is a block diagram of a magnetic actuator. Input electrical energy in the form of voltage and current is converted to magnetic energy. The magnetic energy creates a magnetic force, which produces mechanical motion over a limited range. Thus magnetic actuators convert input electrical energy into output mechanical energy. As mentioned in the figure caption, the blocks are often nonlinear, as will be discussed later in this book.

Typical magnetic actuators include

- Electrohydraulic valves in airplanes, tractors, robots, automobiles, and other mobile or stationary equipment
- Fuel injectors in engines of automobiles, trucks, and locomotives
- Biomedical prosthesis devices for artificial hearts, limbs, ears, and other organs
- Head positioners for computer disk drives
- Loudspeakers

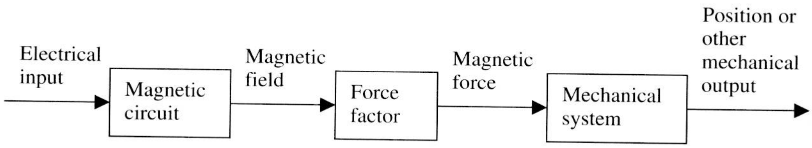

Figure 1.1 Block diagram of a magnetic actuator. The blocks are not necessarily linear. Both the magnetic circuit block and the force factor block are often nonlinear. The force factor block often produces a force proportional to the square of the magnetic field.

- Contactors, circuit breakers, and relays to control electric motors and other equipment
- Switchgear and relays for electric power transmission and distribution

Since magnetic actuators produce motion over a limited range, other electromechanical energy converters with wide ranges of motion are not discussed in this book. Thus electric motors that produce multiple 360° rotations are not covered here. However, "step motors," which produce only a few degrees of rotary motion, are classified as magnetic actuators and are included in this book.

1.2 OVERVIEW OF MAGNETIC SENSORS

A magnetic sensor has the block diagram shown in Fig. 1.2. Compared to a magnetic actuator, the energy flow is different, and the amount of energy is often much smaller. The main input is now a mechanical parameter such as position or velocity, although electrical and/or magnetic input energy is usually needed as well. Input energy is converted to magnetic field energy. The output of a magnetic sensor is an electrical signal. In many cases the signal is a voltage with very little current, and thus the output electrical energy is often very small.

Magnetic devices that output large amounts of electrical energy are not normally classified as sensors. Hence typical generators and alternators are not discussed in this book.

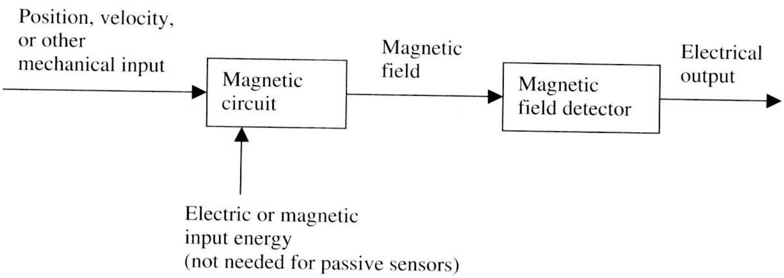

Figure 1.2 Block diagram of a magnetic sensor. The blocks are not necessarily linear.