MAGNETIC STORAGE HANDBOOK

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Second Edition

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FOREWORD

The *Magnetic Storage Handbook* is a thoroughly revised and updated version of Part II of the *Magnetic Recording Handbook* published in 1990. A revised version of Part I has recently been published under the title *Magnetic Recording Technology.*

The extent of the revisions and additions made to the various chapters of the *Magnetic Storage Handbook* have been dictated by how rapidly the subject covered has changed since the earlier handbook was written. Revisions vary from relatively minor (10%) updates to complete rewrites and, in some cases, the recruitment of new authors. The chapters receiving the most extensive revisions are the following:

Data Storage on Rigid Disks. This chapter has been extensively updated to reflect the extraordinary achievements made in recent years in producing disk drives combining high capacity, small size, and low cost.

Data Storage on Flexible Disks. The major additions here cover the progress made in developing high-capacity, replaceable-disk drives designed to backup hard-disk files. These drives combine sophisticated servo systems and advanced flexible media design, and have capacities two orders of magnitude greater than regular 3.5-inch floppies.

Data Storage on Tape. This chapter is entirely new. It covers both fixed and rotating-head tape cartridges, and their primary application in providing large-capacity backup for hard-disk data.

Digital Video Recording. Formerly this subject was covered as a part of the chapter on video recording. It now warrants a newly written, greatly expanded, separate chapter. Digital video recording is now firmly established, with digital video tape recorders becoming increasingly available for both professional and consumer applications.

Digital Audio Recording. This chapter has been completely rewritten.

Other chapters of the *Magnetic Storage Handbook* required less extensive revision. However, where significant technological advances have occurred in recent years, these are covered by the inclusion of the relevant new data, descriptive text, and appropriate references.

PREFACE

The *Magnetic Storage Handbook* provides a comprehensive, up-to-date source of reference information on the major applications of magnetic recording technology for storing computer data, and recording video, audio, and instrumentation information in both analog and digital form. The handbook should be useful to the student as a reference book, but its main purpose is to provide the scientists and engineers in industry with a single source of information on the major applications of magnetic recording, and the related storage products that have been developed.

Magnetic Recording Technology, a recently published companion volume, covers the technologies underlying the various applications. It should also be of interest to industry scientists, particularly those engaged in research and advanced development, and will be of particular interest to the students and staff at the various University Storage Research Centers that have been set up in recent years.

It is some six years since the publication of the *Handbook of Magnetic Recording* that forms the foundation of the present work. The preface written at that time remarked on the rapid growth of the information storage industry and the position occupied by magnetic recording as the dominant, nonstatic memory technology. In the intervening years, the industry has grown at an accelerated pace, but magnetic recording still remains ubiquitous as the technology of choice for reversible, low-cost information storage. The versatility of magnetic recording is still unmatched in providing different storage formats—tapes, stripes, cards, flexible disks, as well as hard disks—a capability that makes magnetic recording uniquely adaptable to a wide variety of data, video, and audio applications, both at the business and consumer level.

The book treats each of the major applications in a separate chapter. The first three chapters deal with applications in the computer area, namely the storage of computer data on rigid (hard) disks, on flexible (floppy) disks, and on tape cartridges. The hard disk is the basis of the large-capacity storage files that are now an essential adjunct to all computers, from the personal computers used in the home to the super computers used in scientific laboratories. The advances made in hard-disk files in recent years are truly remarkable. Capacities of a gigabyte or more that required a stack of a dozen 14-inch diameter disks ten years ago are now readily, and inexpensively, obtainable in a package some four inches square by one-half inch thick. This in turn has stimulated the development of higher performance flexible-disk and tape-cartridge files, since a major use of these removable media files is as backup for hard-disk data. For example, over 100 MB can now be recorded on a single, removable 3-1/2 inch flexible disk. Huge data storage capabilities are available from tape cartridges and cartridges with a capacity of over 100 GB are under development.

The next four chapters cover video and audio recording, in both their traditional and still widely used analog forms, and in their increasingly important and, in the long run, probably dominant, digital forms. In view of their rapid development and increasing presence, digital video recording and digital audio recording are now allotted separate, entirely rewritten chapters, covering both professional or business applications and developments aimed at the consumer market. Another chapter is devoted to instrumentation recording which also uses both analog and digital formats.

The final chapter is concerned with signal and error-correction coding, from fundamental and practical viewpoints. This subject becomes of increasingly wide interest as computer storage applications expand, and digital forms of recording take over from the traditional analog techniques in more and more applications.

SI (Système International d'Unités) units are used throughout. Where other units (such as cgs) are widely used, values expressed in these units are listed in parentheses.

A comprehensive treatise of this scope is possible only by combining the knowledge of many talented people. We greatly appreciate the dedicated efforts of the authors who have contributed their reviews of each branch of the subject and have cooperated in producing an in-depth coverage of this multidisciplined field. We are also indebted to a number of others who provided independent reviews of draft chapters or provided special items of information that assisted us to produce a uniform and up-to-date coverage of the subject matter. These include Tom Howell at Phase Metrics Corporation, J. G. McKnight, and David P. Robinson at Magnetic Reference Laboratory.

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

ADC	analog-to-digital
ADRC	adaptive dynamic range coding
AGC	automatic gain control
ANSI	American National Standards Institute
APC	automatic phase control
ATF	automatic track following
AXP	adaptive cross-parity code
BCH	binary-coded hexadecimal
CAV	constant angular velocity
CCIR	Commité Consultatif Internationale des Radio-Communications
CDS	code word digital sum
CIRC	cross-interleaved Reed-Solomon code
CLV	constant linear velocity
CNR	carrier-to-noise ratio
CRC	cyclic redundancy code
DAB	digital audio broadcasting
DAC	digital-to-analog converter
DASD	direct access storage device
DASH	digital audio stationary head
DAT	digital audio tape
DCC	digital compact cassette
DCT	discrete cosine transform
DPCM	differential pulse-code modulation
DR	density ratio
DRAW	direct read after write
DSL	digital simulation language
DSV	digital sum variation
DTF	dynamic track following
DVTR	digital VTR
ECC	error-correction coding
EDL	edit decision list
EIA-J	Electronic Industry Association of Japan
ELP	extra long play
EPR4	extended partial response Class 4
EPRML	extended partial response, maximum likelihood
ERP	error recovery procedures
FDD	floppy disk drive
FM	frequency modulation
GCR	group coded recording
GF	Galois field
HDA	head-disk assembly
HDDR	high-density digital recording
HDI	head-disk interface
HIP	hot isostatic pressed
HPF	hot pressed ferrite
IBC	International Broadcasting Convention
I/O	input/output
ITI	insert & tracking information
IEC	International Electrotechnical Commission
IRIG	Inter-Range Instrumental Group
ISI	intersymbol interference
ISO	International Standards Organization
LQR	linear quadratic regulator
LRC	longitudinal redundancy code
LSB	least significant bit
M^2	Miller squared
MD	Mini Disc
ME	metal evaporated

MFM	modified frequency modulation
MO	magnetooptical
MOL	maximum output level
MP	metal powder (particle)
MSB	most significant bit
MSS	mass storage system
MTBF	mean time between failures
MTF	modulation transfer function
MUSE	multiple sub-Nyquist encoding
MZM	modified zero modulation
NEP	noise-equivalent power
NPR	noise-power ratio
NRZ	non-return-to-zero
NRZ-ASE	NRZ code with adapted spectral energy
NRZI	modified non-return-to-zero
NRZI-S	synchronized non-return-to-zero
NTSC	National Television System Committee
ORC	orthogonal rectangular code
PAL	phase alternation line
PAM	pulse amplitude modulation
PBS	polarizing beam splitter
PCM	pulse-code modulation
PE	phase encoding
PES	position error signal
PET	polyethylene teraphthalate
PIN	positive intrinsic negative
PLL	phase-locked loop
PMMA	polymethyl methacrylate
PR IV (PR4)	partial response Class IV (4)
PRML	partial response, maximum likelihood
QAM	quadrature-amplitude modulation
R-DAT	rotating-head digital audio tape recorder
RLL	run-length-limited
S-I-NRZI	scrambled and interleaved NRZI code
SCF	single crystal ferrite
SCSI	small computer standard interface
SECAM	sequential color and memory
SER	soft error rate
SFD	switching field distribution
SNR	signal-to-noise ratio
S-NRZ	scrambled NRZ
SP	standard play
SR	shift register
SSR	stretched surface recording
TBC	time base correction
THD	third harmonic distortion
TMR	track misregistration
VCM	voice coil motor
VCO	voltage controlled oscillator
VCXO	voltage controlled crystal oscillator
VFO	variable frequency oscillator
VHS	video home system
VLC	variable length coding
VRC	vertical redundancy code
VSM	vibrating sample magnetometer
VTR	video tape recorder
XOR	exclusive or
ZM	zero modulation
3PM	three-position modulation

Symbols

A	area; an element of GF (2^8)
a	acceleration; arctangent transition parameter
a_i	first digit of the ith digit-pair
$A_m(t)$	mth bit in track t in set A
$A(x)$	polynomial representation of A
B	magnetic induction (flux density)
b	base-film thickness; bit length; length of burst-error; width of guard band
B_i	written data byte in ith position
$\hat{B}_i$	read data byte in ith position
b_i	second digit of ith digit-pair
B_m	maximum induction (flux density)
$B_m(t)$	mth bit in track t in set B
B_r	remanent induction (flux density)

B_s	saturation induction (flux density)
$B(x)$	data polynomial
C	capacitance; capacity (bytes)
c	accumulated dc charge at any digit position in a binary sequence
C_R	damping constant for rotary actuator
C_r	crosstalk
$C(x)$	check polynomial
D	data rate; delay factor; recording density; delay operator
d	head-drum diameter; head-to-medium spacing; minimum run-length of zeros in a binary sequence; RLL code constraint
D_a	areal density (b/mm^2)
D_c	recording density for maximum resolution
d_{eff}	effective head-to-medium spacing
d_i	data bit in the *i*th position in a data stream
D_l	linear (bit) density (b/mm)
D_r	recording density (fr/mm)
D_t	track density (t/mm)
D_u	user density (bytes/mm)
d_0	spacing corresponding to nominal "in-contact" conditions
D_{50}	linear density at which the output falls 50%
E	energy; Young's modulus
e	charge of electron; cycle length of modulo-$G(x)$ shift register; exponent of a polynomial $G(x)$; head output voltage
e_b	back emf
E_i	error pattern in *i*th position
$E(x)$	error polynomial
F	force; system matrix used in servo design; video field frequency
f	frequency; number of data bits in a section
f_c	carrier frequency
F_f	field frequency
f_H	horizontal sync frequency
f_m	maximum frequency
f_{max}	maximum recorded frequency
f_s	signal frequency; sampling frequency
f_{sc}	subcarrier frequency
f_u	color-under subcarrier frequency
$F(\theta)$	particle orientation factor
G	gain
$G(D)$	characteristic polynominal in D
g	gap length
g_{eff}	effective gap length
g_i	*i*th coefficient in the generator polynomial $G(x)$
$G(x)$	generator polynomial
gb	guard band between tracks
GF(2^m)	Galois field of 2^m elements
H	magnetic field
H_b	bias field
H_c	coercivity
H_d	demagnetizing field
H_g	deep gap field
H_p	print field
H_r	remanence coercivity
i	current
j	$\sqrt{-1}$
k	Boltzmann constant; maximum runlength of zeros in a binary sequence; number of information bits in a code word; number of message symbols in a block; ratio of read-to-write widths (w_r/w_w); RLL code constraint; wave number ($2\pi/\lambda$)
k_b	back emf coefficient
k_d	damping coefficient
k_f	actuator force factor
k_x	position gain constant
L	inductance; inductance of voice coil; length of head poles; length of slider
l_{coil}	coil length (actuator)
L_1, L_2	inductance components of voice coil with shorted turns
$L_{1,2}$	coupling inductance of voice coil with shorted turn

M	magnetization; mass; moving mass of actuator
m	dipole magnetic moment; mass; mass of electron; number of data bits; particle magnetic moment
M_p	printed magnetization
M_r	remanent magnetization (remanence); modulation ratio (b/fr)
M_s	saturation magnetization
N	number of particles per unit volume; see distance in units of tracks
n	index of number of tracks; index of mode of vibration; number of bits in a code word; number of message bits; number of symbols in a block; number of turns; quantization bit number
N_d	noise density
n_e	tracks remaining to target track
N_h	number of turns on head
N_l	number of turns on coil
N_s	total number of sectors
N_t	total number of tracks
P	power; print-to-signal ratio
p	number of parity symbols in a block; location of error in a code word; pole-tip length; pressure; volumetric packing density
p_a	ambient (atmospheric) pressure
p_i	coded bit in the ith position in a data word
P_m	maximum print-to-signal ratio
p_{25}	pulse width at 25% amplitude
p_{50}	pulse width at 50% amplitude
$P(A)$	look-ahead parity in zero modulation
$P(B)$	look-back parity in zero modulation
$P(x)$	prime polynomial
Q	information bit redundancy; quality factor in servo design
R	data rate; reluctance; resolution; resistance
r	radial coordinate; radius; number of check bits in a code word
r_d	disk radius
R_m	modulation code rate
S	remanence squareness; synchronization pattern
s	distance between head and permeable layer; number of message bits in a symbol
S_{MTF}	normalized zero-to-peak signal from an NRZ 1010 . . . pattern
S_{sat}	zero-to-peak signal from a saturated region
S_{trans}	normalized zero-to-peak signal from an isolated transition
S^*	coercivity squareness factor
$S(x)$	syndrome polynomial
Sd_m^a	mth cross parity syndrome in Set A
Sd_m^b	mth cross parity syndrome in set B
Sv_m^a	mth vertical parity syndrome in set A
Sv_m^b	mth vertical parity syndrome in set B
T	companion matrix of a polynomial; data period; temperature; tension
t	time; total thickness of medium including substrate; track spacing
T_A	multiplier matrix corresponding to element A
t_a	audio track width
T_c	Curie temperature
t_c	clock window; control track width
t_g	guard band track width
$T_{\max}$	maximum duration between flux changes
$\mathrm{T}_{\min}$	minimum duration between flux changes
$t_{\min}$	minimum track spacing
$\mathrm{TMR}_{W,R}$	write-to-read track misregistration
$\mathrm{TMR}_{W,W}$	write-to-write track misregistration
$\mathrm{TMR}_{3\sigma}$	3σ value of track misregistration
t_p	track pitch

t_r	response time of rigid-disk file
T_s	sampling time
t_{se}	service time of rigid-disk file
t_v	video track width
T_W	detection window
t_w	wait time of rigid-disk file
$T_{\{i\}}$	timing window for $\{i\}$ = RLL and $\{i\}$ = NRZ codes
V	head-to-medium velocity; output voltage
v	data word corresponding to a code word w; mean velocity of actuator
V_c	clip level
V_m	medium velocity (when different from head-to-medium velocity)
v_{max}	maximum velocity of actuator
v_r	velocity of disk
W	code word; transverse displacement; work
w	head width; track width; written mark width
w_a	audio track width
w_c	control track width
w_{eff}	effective track width
w_h	width of head
w_r	read track width
w_t	tape width
w_v	video track width
w_w	write track width
$W(x)$	code-word polynomial
x_d	command to servo
x_e	position error
x_i	data bit in the ith position in a data word; first digit of the ith group of three digits
x/y	rate of a run-length limited code
Y_{coil}	admittance of voice coil
y_i	second digit of the ith group of three digits
Z	impedance
z_i	third digit of the ith group of three digits
α_a	coefficient of thermal expansion of arm
α_s	turns ratio for shorted turn
α_{OT}	off-track constant
Δw	side fringe width; discrepancy between track and playback head
δ	thickness of a magnetic medium
δ_w	side fringe width of read head
δw_w	side fringe width of write head
η	efficiency
Θ	angle of rotary actuator
θ	angular coordinate; video track inclined angle
θ_0	video track inclined angle when tape is stationary
Λ_{trans}	characteristic length of readback from isolated transition
λ	wavelength
λ_c	critical wavelength for maximum resolution
λ_{cutoff}	threshold for modulation transfer function
λ_m	wavelength for maximum print-through
λ_{min}	minimum recordable wavelength
λ_s	magnetostriction coefficient
μ	magnetic permeability
μ_0	magnetic permeability of vacuum
ρ	resistivity
σ	standard diviation
τ	time constant; dibit peak shift
$\bar{\tau}$	average access time
τ_{sk}	seek time
$\bar{\tau}_{sk}$	average seek time
τ_v	dominant time constant of actuator
$\tau(n)$	time to access n tracks
Φ	magnetic flux
ϕ	angular coordinate; gap azimuth angle; magnetic flux
χ	susceptibility
χ_p	print susceptibility
ψ	azimuthal angle
Ω	rotational rate
ω	angular frequency ($2\pi f$)

CONTENTS

CHAPTER 1
INTRODUCTION

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Magnetic recording applications can logically be classified in several ways according to the type of signal to be recorded, the geometric shape of the recording medium, or the type of signal encoding used. Another classification recognizes that the interests of those working in the magnetic recording industry fall into certain well-defined categories. Classification by these categories has been the primary guide in organizing the contents of this book.

Chapters 2 through 4 are concerned with the storage of computer data on rigid disks, flexible disks, and tapes. These applications all use binary digital signals and are usually referred to collectively as *digital recording applications.* Chapters 5 through 9 deal with the recording of video, audio, and instrumentation signals. Each of these applications may use frequency modulation or digital encoding, as well as linear analog recording techniques. Nevertheless, they are usually referred to collectively as *analog recording applications* since they ideally provide an output that is an exact replica of the input. A chapter on signal and error-control coding, which is applicable to all digital recording applications, concludes the contents of this book.

Digital and analog applications differ mainly in terms of the requirements placed upon system performance. The primary requirements of a digital application are high data reliability, fast access to stored data, and low cost per bit. The primary requirements of an analog application are high signal-to-noise ratio, low distortion, and low cost per unit of playing time. Of these differences, the most fundamental is with respect to access time because this largely dictates the mechanical systems and media configurations that are used. In analog applications, the signal is usually in the form of large blocks of serial information—a musical composition, a television show, a transmission of data from a satellite. In such cases, a recording system using a medium in the form of a long length of tape is very suitable. However, in the words of Oberlin Smith, one of the early pioneers of magnetic recording, one disadvantage of a tape is "that if some small portion of the record near the middle has to be repeated there is a good deal of unwinding to do to get at it" (Smith, 1888). This difficulty of achieving quick access to stored data rules out tape media for on-line computer usage. Instead, magnetic media are more attractive in such forms as cards, strips, drums, and most importantly, disks.

Despite the differences outlined above, the two types of applications have much in common. The various species of digital and analog systems evolved over the years from the same origin and still share the same underlying technology—the subject matter of the companion book *Magnetic Recording Technology.* Unfortunately, during the course of this evolutionary process, the technical community working in magnetic recording became more firmly divided than seems reasonable in view of their common ground. This book brings together detailed discussions of all the major magnetic recording applications in one work. By so doing, it is hoped that some of the barriers that exist between workers in different areas will be reduced.

The pace of the evolution of storage technologies is strongly affected by the momentum of the applications that use magnetic and optical recording systems. However, other nonmagnetic optical recording techniques have been introduced into very large consumer applications and provide complementary and competitive storage products. Most significant is the domination of consumer audio recording products by the optically read digitally recorded compact disc. Also, this application has been supported more recently by new digital magnetic recording devices that offer recording as well as playback capability. One device is a digitally recorded magnetic tape, compatible with the popular analog tape cassette (Lokhoff, 1991). The other is a miniature magnetooptical disk drive (Yoshida, 1994).

The evolution of storage devices for the personal computer is also influencing the pace of storage technology development. Primarily, it has greatly accelerated the development of small rigid-disk files. Here, the pace of technology advancement, measured by the storage capacity of small drives, has been increased to the highest level of the 40-year history of disk file development. In turn, this is increasing the use of higher capacity programs in PCs and therefore has put pressure on the development of higher capacity program storage devices. High capacity magnetic floppy disks have been developed to meet this requirement. However, the compact disc technology, called CD-ROM, is finding rapidly increasing application for high capacity PC program storage.

The depth of coverage of recording systems for different applications is weighted by the individual experiences of the authors. Nevertheless, in this book there is collectively a detailed description of the generic magnetic storage technologies used in today's products. For instance, the designs of digital recording channels described for rigid disks and tapes are largely applicable to flexible disks and magnetooptical disks. Likewise, the servo technology discussion on rigid disks applies to flexible and magnetooptical disk systems. While signal coding and error correction coding are mentioned in each of the digital recording chapters, the detailed coverage of the subject is relevant to all applications. Thus, it is hoped that readers will profit from studying chapters that are beyond but related to their specific fields of interest.

The following description of magnetic recording systems will serve as an introduction for those not familiar with magnetic recording.

1.1 EVOLUTION OF MAGNETIC RECORDING SYSTEMS

Every magnetic recording system comprises a means for mechanically transporting recording media and heads with respect to each other, together with a package for the recording medium appropriate to the application. Also included is an electronic signal processor to deliver the signal to the recording head in a form suited to the