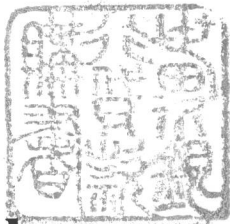


TN 74

P1

V.1

8662608



Precision Frequency Control

Volume 1

Acoustic Resonators and Filters

Edited by

EDUARD A. GERBER

ARTHUR BALLATO

U.S. Army Electronics Technology and Devices Laboratory
Fort Monmouth, New Jersey



1985



ACADEMIC PRESS, INC.

(Harcourt Brace Jovanovich, Publishers)

Orlando San Diego New York London
Toronto Montreal Sydney Tokyo



E8662608

0085286

COPYRIGHT © 1985, BY ACADEMIC PRESS, INC.
ALL RIGHTS RESERVED.

NO PART OF THIS PUBLICATION MAY BE REPRODUCED OR
TRANSMITTED IN ANY FORM OR BY ANY MEANS, ELECTRONIC
OR MECHANICAL, INCLUDING PHOTOCOPY, RECORDING, OR
ANY INFORMATION STORAGE AND RETRIEVAL SYSTEM, WITHOUT
PERMISSION IN WRITING FROM THE PUBLISHER.

ACADEMIC PRESS, INC.
Orlando, Florida 32887

United Kingdom Edition published by
ACADEMIC PRESS INC. (LONDON) LTD.
24-28 Oval Road, London NW1 7DX

Library of Congress Cataloging in Publication Data

Main entry under title:

Precision frequency control.

Includes bibliographies and indexes.

Contents: v. 1. Acoustic resonators and filters --
v. 2. Oscillators and standards.
1. Piezoelectric devices. 2. Electric resonators.
3. Oscillators, Crystal. 4. Acoustic surface wave
devices. I. Gerber, Eduard A. II. Ballato, Arthur.
TK7872.P54P74 1984 621.3815'363 84-14630
ISBN 0-12-280601-8 (v. 1 : alk. paper)

PRINTED IN THE UNITED STATES OF AMERICA

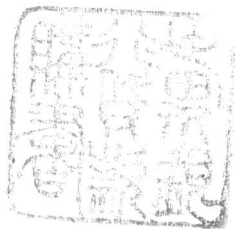
85 86 87 88

9 8 7 6 5 4 3 2 1

Precision Frequency Control

Volume 1

Acoustic Resonators and Filters



Contributors

Numbers in parentheses indicate the pages on which the authors' contributions begin.

ARTHUR BALLATO (285), U.S. Army Electronics Technology and Devices Laboratory, Fort Monmouth, New Jersey 07703

PETER S. CROSS¹ (119), Hewlett-Packard Laboratories, Palo Alto, California 94304

EDUARD A. GERBER² (271, 285), U.S. Army Electronics Technology and Devices Laboratory, Fort Monmouth, New Jersey 07703 (Retired)

LARRY E. HALLIBURTON (1), Physics Department, Oklahoma State University, Stillwater, Oklahoma 74078

JAMES C. KING (147), Sandia National Laboratories, Albuquerque, New Mexico 87185

DALE R. KOEHLER (23, 147), Sandia National Laboratories, Albuquerque, New Mexico 87185

JOHN A. KUSTERS (161), Hewlett-Packard Laboratories, Santa Clara, California 95050

JOEL J. MARTIN (1), Physics Department, Oklahoma State University, Stillwater, Oklahoma 74078

THRYGVE R. MEEKER (47), AT&T Bell Laboratories, Allentown, Pennsylvania 18103

WILLIAM R. SHREVE (119), Hewlett-Packard Laboratories, Palo Alto, California 94304

ROBERT C. SMYTHE (185), Piezo Technology Incorporated, Orlando, Florida 32854

ROBERT S. WAGERS (230), Central Research Laboratories, Texas Instruments Incorporated, Dallas, Texas 75265

¹Present address: Spectra Diode Laboratories, San Jose, California 95134.

²Present address: 11 Community Drive, West Long Branch, New Jersey 07764.

Preface

The editors take pleasure in presenting this two-volume work on precision frequency control. The title encompasses the spectrum of frequency-determining and frequency-selective devices, subject to the constraint imposed by the adjective. A simple circuit consisting of an inductance and a capacitance can function as a frequency-controlling element. Its precision, however, is completely insufficient for modern electronic equipment. Different physical phenomena must be utilized to meet today's requirements. The discussion and explication of these phenomena and their applications are the main purposes of these books.

The aims are twofold: first, to offer a concise compendium of the state of the art to researchers and specialists engaged in a rapidly expanding and complex field of technology. It will enable them to work efficiently in their fields and to develop devices that meet the requirements of the equipment and systems engineer.

A second purpose of the books is to furnish information concerning properties and capabilities of frequency-control devices to users of these devices, such as equipment and systems designers. The volumes will also be very useful for technical managers who will be able to find, in a single publication, a description of the world of precision frequency control, written by experts, and an entree to the full literature of the field.

The idea of these books originated several years ago when the editors recognized that the literature in the field of frequency control was increasing at an explosive rate and that it would be extremely difficult, particularly for a novice in this field, to attain without guidance an essential level of knowledge in a reasonable time. Another incentive for compiling this text is the fact that there is no single book available on the world market that treats all precision frequency-control devices and allows the reader to weigh the advantages or disadvantages of the various technical approaches against one another.

The number of experimental observations and theoretical investigations in the field of precision frequency control has increased steadily over the past 60 years and has led, particularly during the past few years, to a deluge of original publications that is becoming more and more difficult to absorb in its totality, even for the trained specialist. In view of this, our aim is not to attempt to offer a textbook on the subject, but rather to provide a tutorial and coherent treatment of the more recent developments in the field, supported by an extensive literature reference list covering approximately the past fifteen years. The individual chapters are written by experts in their respective specialities. The editors feel that the fundamentals of this field, starting with the seminal works of the Curies, Voigt, Cady, Townes, Ramsey, and others, are very well represented in older textbooks and in many voluminous review papers and handbook articles whose titles the reader will find in the bibliography.

The material of the work is presented in two volumes, "Acoustic Resonators and Filters" (Volume 1) and "Oscillators and Standards" (Volume 2). The reader will find in the introduction to the bibliography, included in both volumes, some suggestions on how to use the chapter bibliographies to best advantage. The 16 chapters of the text can be read independently of one another. Their topics have been chosen to maximize the readability of the book, with lengths governed jointly by the number of publications pertinent to each chapter and by the importance the editors attach to each topic, although obviously it is impossible to discuss in the text all of the more than 5000 publications referenced. The selection of specific areas discussed is to a certain extent subjective, but we feel that they give a good indication of the overall progress in our field.

The reader will find glossaries of letter symbols—whenever necessary—at the beginning of each chapter and, in certain instances, introducing a section. These characters, as well as graphic symbols used in the book, correspond as much as possible to those specified in the following IEEE Standards:

IEEE 260	1978	Letter Symbols for Units of Measurement
IEEE 280	1968	Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering
IEEE 315	1975	Graphic Symbols for Electrical and Electronics Diagrams
IEEE 176	1978	Piezoelectricity
IEEE 177	1966	Definitions and Methods of Measurement for Piezoelectric Vibrators

Copies of these standards may be obtained from The Institute of Electrical and Electronics Engineers, 345 East 47th Street, New York, New York 10017.

The editors wish to express their sincere thanks to the authors of the various chapters for their cooperation and enjoyable collaboration, the editorial and production staffs of Academic Press for their patience and support, Mrs. Carolyn

Clever for her typing, and the personnel of the U.S. Army Electronics Technology and Devices Laboratory, Fort Monmouth, for much encouragement and assistance. They wish to thank, in particular, Mrs. Gloria Gatling for doing a careful and patient job of typing the final version of the bibliography, Miss Betsy Hatch for her computer work, and Mr. Ted Lukaszek for his steady and manifold help prior to and during the preparation of the text. Finally, the editors gratefully acknowledge stimulating discussions over many years with R. D. Mindlin (Columbia University) and R. A. Sykes (AT&T Bell Laboratories), who, by the synthesis of their theoretical and experimental work and by their education of students and colleagues, helped substantially to make a science out of an art in the field of crystal frequency control.

E. A. Gerber
West Long Branch, New Jersey

A. Ballato
Long Branch, New Jersey

Contents of Volume 2

7 Resonator and Device Measurements

by Erich Hafner

List of Symbols

- 7.1 Introduction
 - 7.2 The Crystal Unit and Its Equivalent Circuit
 - 7.2.1 The Resonator-Equivalent Electrical Circuit
 - 7.2.2 Device Properties of the Crystal Unit
 - 7.2.3 The Characteristic Parameters of a Crystal Unit
 - 7.3 Crystal-Resonator Measurements
 - 7.3.1 General
 - 7.3.2 Resonator Measurement Instruments
 - 7.3.3 Measurement Methods
 - 7.4 Summary and Conclusions
- Appendix I: The Generalized Equivalent Circuit
Appendix II: Two-Port Relations for the IEC-444 π Network
Appendix III: Two-Port Relations for a Transmission Bridge

8 Precision Oscillators

List of Symbols for Section 8.1

- 8.1 Bulk-Acoustic-Wave Oscillators
 - by Warren L. Smith*
 - 8.1.1 General Characteristics of Crystal-Controlled Oscillators
 - 8.1.2 Circuit Configurations for Crystal-Controlled Oscillators
 - 8.1.3 Temperature-Control Techniques for Precision Oscillators
 - 8.1.4 Temperature-Compensation Methods for Semiprecision Oscillators
 - 8.1.5 Miniature Integrated-Circuit Oscillators

List of Symbols for Section 8.2

- 8.2 Surface-Acoustic-Wave Oscillators
 - by Thomas E. Parker*
 - 8.2.1 Introduction
 - 8.2.2 The Basic SAW Oscillator—A Physical Point of View
 - 8.2.3 Frequency Stability
 - 8.2.4 Multifrequency Oscillators
 - 8.2.5 Electronic Amplifiers and Other External Components

- 8.2.6 Advantages and Disadvantages of SAW Oscillators
- 8.2.7 Conclusion
- List of Symbols for Section 8.3
- 8.3 Quartz Frequency Standards and Clocks—Frequency Standards in General
by Warren L. Smith
 - 8.3.1 Design Considerations
 - 8.3.2 Measurement and Specification of Frequency Stability

9 Temperature Control and Compensation

by Marvin E. Frerking

- List of Symbols
- 9.1 Temperature Control
 - 9.1.1 Thermal Loss
 - 9.1.2 Warm-Up Considerations
- 9.2 Temperature Compensation
 - 9.2.1 Analog Temperature Compensation
 - 9.2.2 Digital Temperature Compensation
 - 9.2.3 Microprocessor Temperature Compensation

10 Microwave Frequency and Time Standards

by Helmut Hellwig

- List of Symbols
- 10.1 Concepts, Design, and Performance
 - 10.1.1 Historical Perspective
 - 10.1.2 Concept of an Atomic Resonator
 - 10.1.3 Design Principles
 - 10.1.4 Performance Principles
 - 10.1.5 Active and Passive Electronic Systems
 - 10.1.6 Phase-Lock Servos
 - 10.1.7 Frequency-Lock Servos
 - 10.1.8 Electronic Systems
- 10.2 Passive Beam Standards
 - 10.2.1 Beam Generation
 - 10.2.2 Spatial State Selection
 - 10.2.3 Microwave Interrogation
 - 10.2.4 Detection of Atoms
 - 10.2.5 The Cesium-Beam Standard
 - 10.2.6 Other Passive Beam Standards
 - 10.2.7 New Horizons
- 10.3 Gas-Cell Standards
 - 10.3.1 Gas-Cell Principles
 - 10.3.2 Optical State Selection
 - 10.3.3 The Rubidium Gas-Cell Standard
 - 10.3.4 Other Gas-Cell Standards
 - 10.3.5 New Horizons

- 10.4 Hydrogen Masers
 - 10.4.1 Hydrogen-Maser Principles
 - 10.4.2 Active and Passive Masers
 - 10.4.3 Frequency Stability and Accuracy
 - 10.4.4 Other Masers
 - 10.4.5 New Horizons
- 10.5 Other Microwave Frequency Standards
 - 10.5.1 The Ammonia Maser
 - 10.5.2 Trapped Ions
- 10.6 Comparison of Frequency Standards
- 10.7 Applications
 - 10.7.1 Metrology and Science
 - 10.7.2 Technology

11 Laser Frequency Standards

by Rudolf Buser and Walter Koechner

- 11.1 Introduction
- 11.2 The Potential Role of Lasers
- 11.3 Basic Laser Configuration
- 11.4 Stabilization of Lasers
 - 11.4.1 He–Ne Laser Stabilized with a Ne Cell
 - 11.4.2 He–Ne Laser with an I₂ Cell
 - 11.4.3 He–Ne Laser and Methane Absorption Cell
 - 11.4.4 CO₂ Laser with a CO₂ Absorption Cell
- 11.5 Measurement of Optical Oscillation Frequencies
- 11.6 Future Prospects and Problems

12 Frequency and Time—Their Measurement and Characterization

by Samuel R. Stein

- List of Symbols
- 12.1 Concepts, Definitions, and Measures of Stability
 - 12.1.1 Relationship between the Power Spectrum and the Phase Spectrum
 - 12.1.2 The IEEE Recommended Measures of Frequency Stability
 - 12.1.3 The Concepts of the Frequency Domain and the Time Domain
 - 12.1.4 Translation between the Spectral Density of Frequency and the Allan Variance
 - 12.1.5 The Modified Allan Variance
 - 12.1.6 Determination of the Mean Frequency and Frequency Drift of an Oscillator
 - 12.1.7 Confidence of the Estimate and Overlapping Samples
 - 12.1.8 Efficient Use of the Data and Determination of the Degrees of Freedom
 - 12.1.9 Separating the Variances of the Oscillator and the Reference
- 12.2 Direct Digital Measurement
 - 12.2.1 Time-Interval Measurements
 - 12.2.2 Frequency Measurements
 - 12.2.3 Period Measurements

- 12.3 Sensitivity-Enhancement Methods
 - 12.3.1 Heterodyne Techniques
 - 12.3.2 Homodyne Techniques
 - 12.3.3 Multiple Conversion Methods
- 12.4 Conclusion

13 Frequency and Time Coordination, Comparison, and Dissemination

by David W. Allan

- List of Acronyms
- 13.1 Introduction
 - 13.1.1 Historical Perspectives and Methods of Comparison
 - 13.1.2 Time and Frequency Standards
- 13.2 Terrestrial Time and Frequency Comparison or Dissemination Methods
 - 13.2.1 High and Medium Frequency
 - 13.2.2 Low- and Very-Low-Frequency Transmissions
 - 13.2.3 Other Methods
- 13.3 Extraterrestrial Time and Frequency Comparison or Dissemination Methods
 - 13.3.1 Operational-Satellite Techniques
 - 13.3.2 Experimental-Satellite Techniques
 - 13.3.3 Deep-Space Radio-Source Techniques
- 13.4 Coordinate Time for the Earth
- 13.5 Levels of Sophistication and Accuracies for the Users
 - 13.5.1 Typical User Applications
 - 13.5.2 Sophisticated and High-Accuracy Techniques
- 13.6 Summary

14 Other Means for Precision Frequency Control

by Fred L. Walls

- 14.1 Introduction
- 14.2 Low-Frequency Devices
 - 14.2.1 Quartz Tuning Forks
 - 14.2.2 Other Low-Frequency Devices
- 14.3 Microwave Devices
 - 14.3.1 Superconducting Cavities
 - 14.3.2 Dielectrically Loaded Cavities

15 Special Applications

by Fred L. Walls and Jean-Jacques Gagnepain

- 15.1 Microbalances, Thin-Film Measurement, and Other Mass-Loading Phenomena
- 15.2 Measurements of Force, Pressure, and Acceleration
 - 15.2.1 Force
 - 15.2.2 Pressure
 - 15.2.3 Acceleration
- 15.3 Temperature Measurements

16 Specifications and Standards

by Erich Hafner

- 16.1 Specifications
- 16.2 Standards
- 16.3 Practices in the United States
- 16.4 International Standardization

Bibliography

by Eduard A. Gerber and Arthur Ballato

Introduction
General Bibliography
Chapter Bibliographies

Introduction

The history of precision frequency control provides a good example of how technological maturity follows upon the prior accomplishment of scientific groundwork. The foundations of modern frequency control began with discovery of the piezoelectric effect by the brothers Curie in 1880, which found theoretical treatment in Voigt's classic book (1910). Founded on these accomplishments, the development of devices using the piezoelectric effect started during World War I and has proceeded since at an accelerating rate. Quartz crystals used for frequency control developed from rather simple, unevacuated, pressure-mounted units of the 1920s and 1930s to the present highly sophisticated plated units operating in ultrahigh vacua with temperature-compensating or temperature-controlling arrangements. Influences of the environment, such as mounting structure, pressure, and acceleration, have been greatly reduced by using doubly rotated crystal plates. Similarly, great progress has been made in the development of frequency-control devices based on atomic or molecular processes since Essen built and described the first cesium-beam frequency standard in 1957. They have progressed from the original 8-ft giant to the currently commercially available equipment of modest size and weight.

It is no accident that the flowering of our field has coincided with the advent of the space age. No stretch of the imagination is required to see the demands placed on oscillator stability by rocket and satellite environments; and in few applications is the need for precision so severe. Concurrently, similar requirements were imposed in the fields of communication and guidance systems, both commercial and military. For instance, systems for frequency- and time-division multiplex communication, satellite-assisted positioning, as well as remote surveillance and collision avoidance, would be impossible without precision frequency-control and timing devices.

In the dozen years from the launching of the first artificial satellite about the earth to the first manned lunar landing, the frequency-control field and its correlate areas of selection, signal processing, timing, and time distribution experienced an enormous period of development and growth. The advances made during this time turned out, in retrospect, to be only a prelude to the developments of the next decade. The interval following the first Apollo landing initiated what might justly be called the golden age of frequency control. The editors made no predictions as to the extent and duration of this exciting period—certainly it is continuing; but one may well question if we shall soon see a decade in which the development of both accuracy and precision will experience such favorable conditions as have been met within the area of frequency control.

The attribute “precision” in the title restricts the contents of this work to those devices whose Q value and frequency stability far exceed that of an ordinary LC circuit. Consequently, the reader will not find ceramic resonators and filters discussed. Material on polycrystalline and similar devices is included only if it bears on the behavior of high- Q devices (e.g., the theory of vibration of anisotropic bodies). On the other hand, superconductive LC devices with their high Q are properly included. One other remark regarding selection of material is pertinent: The main application of bulk-wave monocrystalline devices is to frequency control, whereas surface-acoustic-wave devices are being used in many other fields. We therefore discuss the fundamental properties of bulk-wave devices and their materials to a fuller extent. As far as surface-wave monocrystalline devices are concerned, only those aspects of material and resonator properties considered pertinent to precision frequency control are covered.

Contents



CONTRIBUTORS	ix
PREFACE	xi
CONTENTS OF VOLUME 2	xv
INTRODUCTION	xxi

1 Properties of Piezoelectric Materials

List of Symbols	2
1.1 An Overview	2
<i>by Larry E. Halliburton and Joel J. Martin</i>	
1.1.1 Structural Requirements	3
1.1.2 Electroelastic Relations	4
1.1.3 Materials of Current Interest	10
1.2 Physical Properties of Quartz	23
<i>by Larry E. Halliburton, Joel J. Martin, and Dale R. Koehler</i>	
1.2.1 Crystallography	23
1.2.2 Crystal Growth and Extended Defects	25
1.2.3 Point Defects	32
1.2.4 Thermal Properties	39
1.2.5 Material Evaluation Techniques	40

2 Theory and Properties of Piezoelectric Resonators and Waves

List of Symbols for Sections 2.1 and 2.2	48
2.1 Bulk Acoustic Waves and Resonators	50
<i>by Thrygve R. Meeker</i>	
2.1.1 Introduction	50
2.1.2 Basic Quasi-Static Theory of a Piezoelectric Elastic Material	52

2.1.3	Linear Theory	53
2.1.4	Nonlinear Theory	56
2.1.5	The Christoffel Plane-Wave Solutions for the Linear Quasi-Static Piezoelectric Crystal	58
2.1.6	Thickness Modes	63
2.1.7	Contour Modes in Thin Plates and in Thin and Narrow Bars	77
2.1.8	Theory for Combined Thickness and Contour Modes	90
2.1.9	Electrical Effects in Piezoelectric Resonators	102
2.1.10	Equivalent Electrical Circuits for Piezoelectric Resonators	103
2.1.11	Properties of Modes in Crystal Resonators	107
2.1.12	Piezoelectric Materials	107
2.1.13	Conclusion	110
2.2	Properties of Quartz Piezoelectric Resonators <i>by Thrygve R. Meeker</i>	110
2.2.1	Temperature Coefficient of Resonance Frequency	110
2.2.2	Dependence of Crystal Inductance on Temperature	112
2.2.3	Tabulation of Properties of Quartz Resonators	113
2.2.4	Conclusion	113
	List of Symbols for Section 2.3	118
2.3	Surface Acoustic Waves and Resonators <i>by William R. Shreve and Peter S. Cross</i>	119
2.3.1	Introduction	119
2.3.2	Resonator Design	126
2.3.3	Fabrication	137
2.3.4	State-of-the-Art Performance	140
2.3.5	Conclusion	144

3 Radiation Effects on Resonators

by James C. King and Dale R. Koehler

3.1	Introduction	147
3.2	Radiation Effects and Modeling	148
3.2.1	Substitutional Al^{3+} Defect Center	148
3.2.2	Frequency Changes	149
3.2.3	Optical Effects	153
3.2.4	Elastic Modulus Changes	153
3.3	Dynamics of Radiation Effects	154
3.3.1	Hydrogen and Transient Effects	154
3.3.2	ESR and IR Studies	155
3.3.3	Trap Characterization	156
3.3.4	Material Quality and Anelastic Losses	157
3.3.5	Thermal Effects	158

4 Resonator and Device Technology

by John A. Kusters

4.1	Resonator Material Selection	161
4.2	Sawing	163
4.2.1	Natural Quartz	165
4.2.2	Cultured Quartz	166