Design of Crystal and Other Harmonic Oscillators

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A Wiley-Interscience Publication
JOHN WILEY & SONS
New York • Chichester • Brisbane • Toronto • Singapore

Library of Congress Cataloging in Publication Data:

Parzen, Benjamin, 1913-
Design of crystal and other harmonic oscillators.
"A Wiley-Interscience publication."
Bibliography: p.
Includes index.
1. Oscillators, Electric. 2. Oscillators, Crystal.
I. Ballato, Arthur. II. Title.
TK7872.07P26 1983 621.3815'33 82-13620
ISBN 0-471-08819-6

Printed in the United States of America

10 9 8 7 6 5 4 3

To the Memory of
My Father and Mother

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Preface

Oscillators are an integral part of electronic equipment in many fields—communication, navigation, data processing, and so on. The harmonic oscillator is the type of oscillator with the greatest stability. Probably millions or billions of this type of circuit are in existence and more will be needed in the future. It is therefore important to gain as much knowledge as possible about harmonic oscillators, and this book has been written to help this.

As the title signifies, the book treats oscillators producing quasi-sine-waves whose frequencies are determined by networks of two types of energy storage elements—such as inductors and capacitors, or the equivalent, for example, crystal resonators.

Despite the long history of harmonic oscillators, including crystal oscillators, their successful design still depends largely on the skill and experience of the designer, and usually proceeds in a "cut and try" fashion. This has been greatly influenced by the well-known fact that it is not at all difficult to assemble a configuration that will oscillate somehow, since useful oscillations are produced over a very wide range of parameters. However, the procedure required to make the oscillator satisfy prespecified conditions is not at all easy and has not been successfully developed. This book attempts to correct this situation.

The literature on harmonic oscillators is voluminous, but has made very little progress toward achieving a practical, systematic, and quantitative design procedure over a wide frequency range. Examination of the literature shows that it generally falls into the following categories:

1 General qualitative and quantitative exposition of oscillator theory with little attention paid to its practical application to produce oscillators. The exposition may be at a relatively elementary or a very advanced level.
2 Qualitative and perhaps some quantitative descriptions of oscillator theory including specific circuit diagrams for particular designs, with some sketchy statements about the performance of these designs but with no clue as to how the circuit diagrams were derived.

3 Exploration of the effect on frequency variation by the variation of some circuit parameter, without corresponding attention to the effect of the same variation upon the remaining characteristics of the oscillator, for example, amplitude.

The literature thus far lacks a relatively simple and direct design procedure which bridges the gap between theory and practice, and which transforms oscillator performance requirements into circuit component values. This book attempts to significantly contribute to the realization of such a procedure.

In this book the literature and the writer's theoretical work and practical experience are gathered together and modified by suitable assumptions and approximations to synthesize a straightforward, unified, and direct design technique for the most popular configurations. In achieving the result, the following criteria were followed:

1 The technique should involve only direct manipulation of equations and relatively easily determinable values for the approximate values of the parameters of these equations. Graphical procedures are therefore excluded, and the technique can be used with simple computers or with the more powerful hand-held calculators. This includes the necessary algorithms for such programming.
2 Only a minimum of information about the various components, particularly the transistor, should be necessary for an approximate design, provided that the resonator properties are reasonably well known.
3 The design technique should be useable by people having only moderate skill and knowledge and lacking the understanding of the derivation of the technique, such as medium-grade electronics technicians. On the other hand, personnel of much greater skill, such as engineers, should be able to study the derivation, including the assumptions and approximations, learn much about the behavior of oscillators, and, hopefully, go on to advance the state of the art and improve the technique.

The basis of the technique is the judicious combination of fields of knowledge, which have long been available, and some recently formulated unpublished work by the writer. These fields of knowledge are:

1 Linear circuit theory.
2 The nonlinear behavior, outlined in Chapters 2 and 6, of practically all silicon bipolar transistors under the idealized conditions described.

These subjects are combined while making the important and simplifying assumption that the circuit operates independently on each component of the current and/or voltage, fundamental, and harmonics, without interference from each other. The purist can rightly object to this assumption because of the obvious nonlinearity, but, since only an approximate solution is acceptable, it is heuristically permissible.

The main reason for the lack of satisfactorily simple conversion of theory into practice has been the great complexity of the reasonably accurately detailed oscillator model, due to its highly nonlinear nature and the resulting insufficient knowledge concerning the magnitude of the parameters in the model. It was, therefore, necessary to simplify the models by suitable assumptions and approximations, self-evident in theory or justifiable by experience. It is obvious that such assumptions and approximations can only result in approximately accurate designs. However, it is questionable whether a more accurate and therefore more complicated procedure will yield a more usefully accurate design in view of the tolerances which exist for all the components of the oscillator and particularly the wide variations of the transistor parameters. In addition, the calculated design will always require modification to accommodate the standard values of available components, and to compensate for the unknown stray elements inherent in the layout which cannot be included in the calculations.

The traditional design technique in industry often consists of the following steps:

1 The designer receives the set of specifications outlining the oscillator requirements.

2 The designer examines the firm's past experience and locates the previous design closest to the design now requested.

3 Depending upon his or her skill and knowledge, the designer will, on paper, alter some of the components of this previous design to more closely suit the new requirements. Very often this step is omitted and step 4 is done immediately.

4 The unit of step 3, called the "prototype," is then built.

5 The designer proceeds to adjust the component values until the desired performance is achieved. The time duration and degree of success of this step depends largely on the skill, intuition, and experience of the designer. Often enough, this is done in more or less a random fashion, and is therefore very costly. Catastrophe results when a large number of identical units based upon this design are desired, as each unit will then require more or less extensive individual adjustment.

The design technique presented in this book is the following:

1a The designer receives the set of specifications outlining the oscillator requirements.

2a The designer selects the oscillator circuit type suitable for the application.

3a Using the algorithm, which presumably has been programmed into a computer or calculator, for that circuit type, provided in this book, the analytic parts of the book are for readers who already have considerable knowledge of electronics and some knowledge of oscillators. For convenience, background material in circuit concepts and transistors is briefly presented, but only as final results and references are made to the literature where more extensive treatment may be obtained. Several different methods of analysis of oscillators are developed and the advantages of each explained. But in every case of application, except for didactic purposes, the tendency is to give preference to that method which entails the least work in solving that particular problem.

The goal of this book is not to present typical circuits with component values, but to develop a logical procedure for calculating the component values. For this reason, the component values are omitted in circuit diagrams except in design examples.

The book is concerned with the steady-state conditions and only incidentally mentions the transient state. Other subjects omitted are temperature compensation, oven design, and VCOs. RC and relaxation oscillators are excluded, as they are not harmonic oscillators.

I should like to express my sincere appreciation to the staff, and particularly to Martin Bloch, of Frequency Electronics, Inc., where I developed much of the original material and conceived the idea of writing the book; to Arthur Ballato, for his contribution of the chapter on piezoelectric resonators and for his invaluable assistance in obtaining background material from the more inaccessible domestic and foreign sources; to the faculty and staff of the Department of Electrical Engineering and Computer Sciences at the University of California at San Diego, where I wrote most of the book; and to my brother Emanuel for his advice and encouragement.

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San Diego, California
November 1982