MECHANICAL FILTERS IN ELECTRONICS

ROBERT A. JOHNSON

WILEY SERIES ON FILTERS

DESIGN, MANUFACTURING AND APPLICATIONS

Library of Congress Cataloging in Publication Data:

Johnson, Robert A., 1932–
Mechanical filters in electronics.

(Wiley series on filters)
Includes index.
1. Mechanical filters (Electronic engineering)
I. Title. II. Series.
TK7872.F5J66 1982 621.3815′32 82-10922
ISBN 0-471-08919-2

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

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Editors: Robert A. Johnson and George Szentirmai

Mechanical Filters in Electronics
Robert A. Johnson

LC - Filters: Design, Testing, and Manufacturing
Erich Christian

To my wife Lois, whose support was essential;
and to those who use their knowledge to bring peace,
dignity, and a better life to the world's people

SERIES PREFACE

The primary objective of the Wiley Series on Filters is to bring together theory and industrial practice in a series of volumes written for filter users as well as those involved in filter design and manufacturing. Although this is a difficult task, the authors in this series are well qualified for the job. They bring both strong academic credentials and many years of industrial experience to their books. They have all designed filters, have been involved in manufacturing, and have had experience in interacting with the filter user.

Each of the books covers a wide range of subjects including filter specifications, design, theory, parts and materials, manufacturing, tuning, testing, specific applications, and help in using the filter in a circuit. The books also provide a broad view of each subject based on the authors' own work and involvement with filter experts from around the world.

The most outstanding feature of this series is the broad audience of filter builders and users, which it addresses. This includes filter research and development engineers, filter designers, and material specialists, as well as industrial, quality control, and sales engineers. On the filter user's side, the books are of help to the circuit designer, the system engineer, as well as applications, reliability, and component test experts, and specifications and standards engineers.

ROBERT A. JOHNSON
GEORGE SZENTIRMAI

PREFACE

The purpose of this book is to describe the design, manufacturing, and use of mechanical filters to practicing engineers. The audience I am addressing includes people involved in filter research, design, and manufacturing, in addition to those involved in the use of filters: systems engineers, circuit designers, applications engineers, and reliability and test engineers. Because this is the first comprehensive book written on mechanical filters in the western world, I have given it an international slant to make it helpful to those working outside of the United States.

This book was written for both the skilled filter designer and the person who has a basic knowledge of electrical engineering. There is enough theory developed to enable the person who is new to mechanical filters to understand how mechanical filters work, as well as how they are manufactured, specified, tested, and used. For the person knowledgeable in mechanical filters, the book provides access to a considerable amount of new and difficult-to-obtain information and also can be used as a quick reference.

In this book I use filters that are presently being manufactured to illustrate basic concepts. In this way, while learning the fundamentals, the reader is also made aware of the state of the art in mechanical filter technology. Also, because this is a "real world" book I have taken some risks by expressing value judgments based on 25 years of electromechanical filter design, but I have usually warned the reader when I have done so.

Because the book's wide audience is composed of filter builders and users, I have worked toward making each chapter as independent of the others as possible. For example, this allows the filter user who is writing a specification to start with Chapter 8 and avoid having to read the chapters on designing a mechanical filter. At the same time, the chapters that are heavy with design are not compromised. I would suggest, though, that Chapter 1 be read by everyone.

The main thrust of Chapter 1 is to provide answers to such questions as, what are mechanical filters, and what are their characteristics? Chapter 2, which deals with transducers, is important in that it bridges the electrical/mechanical gap through the use of analogies and equivalent circuits. For a filter designer the entire chapter is essential, whereas the nonspecialist can skip the equations and read to the section on magnetostrictive transducers.

At that point, the nonspecialist can continue or can jump to the section on piezoelectric ceramics, which parallels the magnetostrictive section.

Chapter 3, on resonators and coupling elements, is important for the filter designer (in particular the concept of equivalent mass), but only the first few pages and the section on coupled resonators need to be read by the filter user. Chapter 4, on circuit design methods, is of interest to the filter user because it deals with the question of the conditions for electrical tuning. Also the figures illustrate the various transducer/resonator/coupling combinations used by mechanical filter manufacturers. Since the material of Chapter 4 is long and detailed, the nonspecialist who reads all of it deserves a great deal of praise.

Chapters 5 and 6 are the nuts and bolts of the mechanical filter technology and are of value to both the filter designer and user. These chapters are of particular value to applications and reliability engineers, who have responsibility for seeing that filter components selected are reliable and will withstand expected environmental stresses.

Chapter 7, applications of mechanical filters, discusses the various systems in which mechanical filters are used, and therefore is of interest to applications and systems engineers and to equipment designers. Chapter 8, on specifying and testing mechanical filters, is of help to everyone, from the filter designer to the filter user's incoming-inspection test technician.

The chapter on using mechanical filters, Chapter 9, was written for those who employ mechanical filters in their equipment. This chapter completes the cycle that started in Chapter 1 with the filter user's question of what filter to choose, and proceeded through subsequent chapters to cover subjects such as specifications, design, manufacturing, and testing.

ROBERT A. JOHNSON

Tustin, California
December 1982

ACKNOWLEDGMENTS

This book was made possible by those people who were willing to share their time and their ideas with me. They have become my friends and so the distinction between our friendship and our professional relationship has blurred. Each of these people has also shared my dream of a free exchange of ideas among technical people throughout the world. This has been true of my supervisors, Rich Muret, Jack Graham, and Wes Peterson, who created a work climate that allowed for this open exchange of ideas. I also thank my co-workers whose help started 25 years ago when Herb Lewis spent his lunch hours teaching me filter theory. At the present time I have been getting technical help and encouragement from Bill Domino, Pete Ysais, Fred Fanthorpe, Lee Cornet, and Don Havens.

I also want to express my appreciation to Gabor Temes, who taught me about filter design with transformed variables and started me in my first book writing; to Carl Kurth, who involved me in IEEE technical activities; to Desmond Sheahan, who worked with me in building bridges to other parts of the world; and to George Szentirmai, my Wiley Filter Series co-editor, who has been a teacher and a support to me for many years.

Also, I want to thank my international friends for their contributions to this book. Masashi Konno was my first contact outside of the United States and he has been a wonderful friend and source of help over the past two decades. I have been privileged to write papers with Manfred Börner and Kazuo Yakuwa and discuss both design and factory concepts with Takeshi Yano and Tasuku Yuki. A little more than ten years ago I met Alf Günther, who has become a friend, history teacher, and always a willing source of technical help. I want to thank also Hans Schüssler, Josef Deckert, Francesco Molo, and Satoru Fujishima for helpful discussions, correspondence, and factory visits. It has been a privilege to know Josef Trnka, Herbert Ernyei, and Franciszek Kamiński whose work, due to space limitations, has been somewhat neglected in this book. Thanks also to Tetsuro Takaku, Izumi Kawakami, Yasukaza Kawamura, and Yasuo Koh for their help; and to Yoshi Tomikawa who taught me about rigid-body modes and mechanical equivalent circuits while he was in the United States.

Finally, thanks to Dot Hopkins and Jan Chantland for their help in typing the manuscript; our factory and marketing people; and again to Wes Peterson, who, because of the special person he is, made this book possible.

R.A.J.

CONTENTS

Chapter One

INTRODUCTION

This is a book about mechanical filters—or more precisely, electromechanical bandpass filters. The term *electromechanical* comes from the transformation, within the filter, of electrical signals into mechanical energy, and after the filtering takes place, the transformation of the remaining signals back into the original electrical form. The term *bandpass* means that the filter will pass a band (a spectrum) of frequencies and attenuate frequencies outside of that band. This description of electromechanical filters is not unique to mechanical filters. There are other electromechanical bandpass filters: crystal filters, ceramic filters, and surface acoustic wave (SAW) filters, so we must further define what we mean by the words *mechanical filter*. We will do this by comparing the mechanical filter to the other electromechanical filters.

A mechanical filter is composed of acoustically (mechanically) coupled mechanical resonators. This differentiates a mechanical filter from lumped-component quartz-crystal filters or ceramic filters that are composed of electrically coupled resonators. A mechanical filter has bulk or lumped resonators that are usually wire coupled, which distinguishes it from acoustically coupled monolithic crystal filters and ceramic filters, which use two or more resonators on a single substrate. A mechanical filter is differentiated from a SAW filter by the fact that signals in a SAW filter are propagated in only one direction, whereas signals in a mechanical filter are allowed to propagate back and forth between the input and the output.

A mechanical filter also is a passive analog component; it requires no external power sources or external clocks, and it processes analog rather than digital data. This differentiates the mechanical filter from active, switched capacitor (SC), charged coupled device (CCD), and digital filters.

BASIC PRINCIPLES

Understanding the operation of a mechanical filter involves an understanding of basic principles of physics, circuit theory, and vibration theory, along with a familiarity of electromechanical transducer concepts. It is this breadth of necessary knowledge that frightens people when confronted with understanding the mechanical filter. Therefore, when talking to an electronics engineer, the mechanical filter designer usually talks in terms of electrical analogies and equivalent circuits, and when discussing mechanical filters with a mechanical engineer, they will probably talk about springs and masses.

A transition between the two disciplines can be made with motor and loudspeaker examples (electrical-to-mechanical) and generator and phonograph pick-up examples (mechanical-to-electrical). The motor-generator concepts are helpful in understanding how impedances are reflected through electromechanical transducers. For example, when the electrical output terminals of a generator are shorted, the mechanical impedance (ratio of torque to angular velocity) across the armature suddenly increases. Loudspeaker and phonograph pick-up concepts are helpful in understanding the transduction of many signals having various amplitudes and frequencies. Because of frequency response limitations of electromechanical transducers, loudspeakers and phonograph pick-ups act as electrical-to-mechanical and mechanical-to-electrical bandpass filters. The broader the passband and the flatter the amplitude response in the passband, the better the fidelity.

Elements of a Mechanical Filter

The mechanical filter is a device composed of electrical, electromechanical, and mechanical elements combined in such a way that bandpass filtering takes

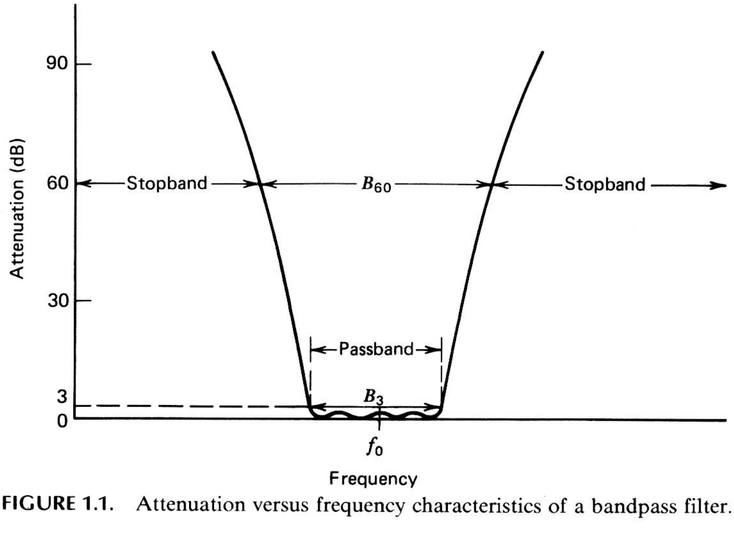

FIGURE 1.1. Attenuation versus frequency characteristics of a bandpass filter.

place. Figure 1.1 shows the frequency response of a mechanical filter. The curve corresponds to the voltage, expressed in dB, at the output terminals of the filter. The input signal, which drives the source resistance and filter, is a constant voltage, variable-frequency sinusoidal wave. The attenuation of the input signal is measured with respect to the maximum voltage output. The difference between the two frequencies corresponding to 3 dB attenuation is the 3 dB bandwidth B_3. The region between the two 3 dB frequencies is the filter passband. The difference between the 60 dB attenuation frequencies is the 60 dB bandwidth B_{60}. The region outside the 60 dB points is the stopband. The ratio of B_{60} to B_3 is the shape factor of the filter. The center frequency f_0 is often defined as the frequency midway between the 3 dB attenuation frequencies. The ratio of B_3 to f_0 is the fractional bandwidth of the filter. Having defined the frequency characteristics of the mechanical filter, let's now look at the elements, which when properly combined achieve a desired response.

Figure 1.2 shows the electrical, electromechanical, and mechanical elements used in a mechanical filter. The electrical tuning element resonates with the electrical reactance of the electromechanical transducer but is only used in so-called intermediate-band and wideband filters. The transducer is either magnetostrictive or piezoelectric, and when alone or when attached to a metal rod or bar, it resonates at a frequency within the filter passband. The transducer drives a system of wire-coupled resonators which, in turn, drives the output transducer and electrical tuning coil or capacitor. The terminating resistors R represent the resistance of the input (source) and output (load) circuits. It is necessary to terminate the filter with resistance in order to achieve a flat or moderate ripple passband response. All of the filter components have linear and bilateral characteristics, so different amplitude and frequency signals can be treated independently or simply added as they propagate in both directions between the filter input and output resistors.

So far, we have treated the mechanical filter in very general terms. Let's next look at a specific filter and trace a signal from the generator to the load resistor. Figure 1.3 shows a disk-wire mechanical filter that employs magnetostrictive ferrite transducers. Looking at Figure 1.3, electrical current I from the voltage generator flows into the resonating capacitor C_R and the transducer coil. Current through the coil produces a magnetic field which passes through the ferrite rod causing the ferrite to vibrate at the frequency of the generator

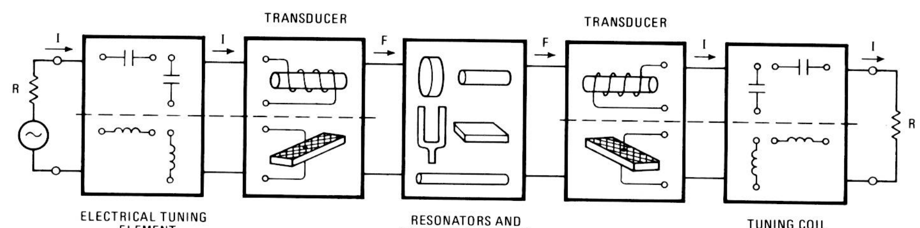

FIGURE 1.2. A mechanical filter circuit showing a variety of its primary elements. (Reprinted from *ELECTRONICS*, Oct. 13, 1977, copyright © McGraw-Hill, Inc., 1977. All rights reserved.)

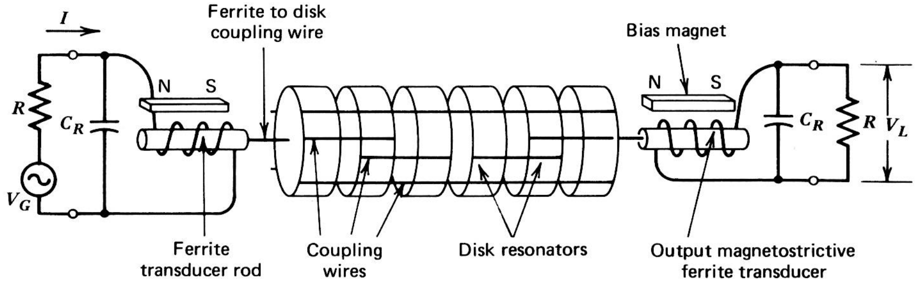

FIGURE 1.3. Essential elements of the six-disk mechanical filter shown in Figure 1.4.

signal. The change in dimensions and resultant vibration due to a changing magnetic field is called *magnetostriction*. This vibration is coupled to the first disk resonator by means of a small wire. Mechanical energy is coupled between disks by wires welded to the circumference of each disk. Vibrations from the end disk and coupling wire excite the output transducer. Strains in the output transducer produce an alternating magnetic field which induces a voltage V_L across the coil and load resistor R. Although we described the signal as flowing from the input to the output, it should be remembered that under steady-state conditions, energy is passing in both directions. Figure 1.4 shows the actual disk-wire mechanical filter.

Turning to Figure 1.5, we see an electrical equivalent circuit of the disk-wire mechanical filter. The mechanical components—the springs, masses, and damping elements—have been transformed to their electrical equivalents by means of the direct, or mobility, analogy. If we were to make a digital-computer frequency-response analysis of the inductor-coupled network in Figure 1.5, we would obtain a curve similar to that in Figure 1.1. That is evident to a person skilled in basic filter theory but far from obvious to the novice.

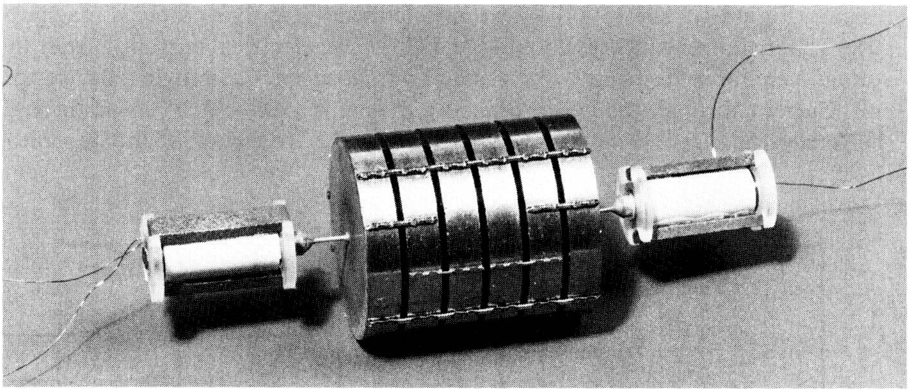

FIGURE 1.4. Mechanical filter used in FDM telephone systems. (Courtesy of Rockwell International, USA.)