Preface

Attenuation of vibration and noise constitutes a growing concern in today's human activities. For more than forty-five years, it was realized that passive attenuation of vibration and noise via dedicated absorbers has limits and the concepts of active vibration and noise control have emerged. Active vibration and noise control are strongly related to control methodology even if in the past the control community was not the driving force in this field. Almost from the beginning, the uncertainties and changes in the characteristics of the environment (vibrations, noise, system dynamics) have prompted the idea of using an adaptive approach in active vibration or noise control. Addressing some of these issues from a robustness point of view is a much more recent tendency in the field. Practical experience has shown also the limits of using only physical models for designing active vibration or noise control systems bringing to light the need of dynamic model identification directly from input/output data.

The aim of this book is to approach the design of active vibration control systems from the perspective of today's control methodology. In that sense the first objective is to formulate from the beginning the various design problems encountered in active vibration control as control problems and search for the most appropriate control tools to solve them. Experimental validation of the proposed solutions on relevant test benches is another issue addressed in this book. To make these techniques widely accepted, an appropriate presentation should be given, eliminating theoretical developments unnecessary for the users (which can be found elsewhere) and focusing on algorithms presentation and their use. Nevertheless, the proposed solutions cannot be fully understood and creatively exploited without a clear understanding of the basic concepts and methods and so these are given in-depth coverage.

The book is mainly based on the work done in a number of PhD theses prepared at Gipsa-lab (INPG/UJF/CNRS), Grenoble, France:

- A. Constantinescu "Robust and adaptive control of an active suspension" [59];
- M. Alma "Adaptive rejection of disturbances in active vibration control" [11];
- T.B. Airimițoaie "Robust control and tuning of active vibration control systems" [4]; and

- A. Castellanos-Silva "Feedback adaptive compensation for active vibration control in the presence of plant parameter uncertainties" [47];

as well as on the results of an international experimental benchmark on adaptive feedback vibration attenuation [146].[1]

All the methods and algorithms proposed in the book have been thoroughly validated experimentally on three test benches (designed by Mathieu Noé from Paulstra - Vibrachoc, Paris) and located at the Gipsa-lab (INPG/UJF/CNRS) in Grenoble, France.

The idea of writing this book arose when I was asked to present a tutorial on control tools for active vibration control at the 4ème Colloque francophone "Analyse Vibratoire Expérimentale", Blois, France, November 2014 (Chairman: Roger Serra, INSA Centre Val de Loire). On that occasion, I listed the concepts, methods and algorithms that have been used to provide solutions for active damping, feedback and feedforward attenuation of vibration. All these concepts and methods, which form the basis of the solutions proposed, are taught separately in various control courses or can be found in various books, so it appeared reasonable to try to bring them together and present them accessibly for those interested in using modern control concepts in active vibration control. With this knowledge to hand, the various solutions proposed for active vibration control can be easily understood and used. The need for including experimental results in order to allow readers to assess the potential of the various solutions is obvious.

Three major problems are addressed in the book:

- active damping (for improving the performance of passive absorbers);
- adaptive feedback attenuation of single and multiple tonal vibrations; and
- feedforward and feedback attenuation of broad-band vibrations.

With few exceptions the analytical details have been skipped and reference to the appropriate journal papers has been made. The focus is on enhancing motivations, algorithms presentation and experimental evaluations.

Once I had a clear view of how this book should be, I solicited the collaboration of Tudor-Bogdan Airimițoaie, Abraham Castellanos-Silva and Aurelian Constantinescu in order to realize it.

Website

Complementary information and material for teaching (simulators, algorithms and data files) can be found on the book website: http://www.landau-adaptivecontrol.org/

[1] http://www.gipsa-lab.grenoble-inp.fr/~ioandore.landau/benchmark_adaptive_regulation/

Expected Audience

The book may be considered as the basis of a course for graduate students in mechanical, mechatronic, industrial electronic, aerospace and naval engineering.

Part of the book may be used to illustrate the applicability of various graduate control courses (system identification, adaptive control, robust control).

The book is of interest for practising engineers in the field of active vibration control wishing to acquire new concepts and techniques well validated in practice.

The book is also of interest for people concerned with active noise control, since the techniques presented can, to a large extent, be used for active noise control too. Researchers in the field of active vibration control may also find inspiring material that opens paths toward new developments.

About the Content

The book is divided into six parts. The introductory part (Chapters 1 and 2) presents the problems addressed in the book and the test benches used for experimental validation.

The second part is dedicated to the presentation of the control techniques used effectively in active vibration control. Chapter 3 discusses the discrete-time model representation used throughout the book. Chapter 4 is dedicated to the presentation of the parameter adaptation algorithms that will be used throughout the book. Chapter 5 gives a compact presentation of system-identification techniques focusing on the specific algorithms used in active vibration control. Chapter 6 illustrates the use of these identification techniques for identifying the dynamic models of the three test benches already presented in Chapter 2. Chapter 7 reviews basic methods for the design of digital controllers that have been used in active vibration control. Chapter 8 provides effective solutions for identification in closed-loop operation allowing the improvement of the dynamic models identified in open-loop operation or re-tuning of the controller. Chapter 9 addresses the problem of controller order reduction because the result of the design is often a high-order controller since on one hand the models of the system are of high dimension and on the other the robustness constraints contribute to the increase of the order of the controller.

The third part is dedicated to the problem of active damping (Chapter 10). The design aspects and the experimental evaluation are discussed in detail.

The fourth part is concerned with the robust and adaptive attenuation of vibrations by feedback. Chapter 11 treats the problem of robust feedback attenuation of narrow-band (tonal) disturbances subject to limited frequency variations. Chapter 12 introduces the basic algorithm for adaptive attenuation of narrow-band disturbances. Experimental evaluations on two test benches are presented. Performance comparison of robust and adaptive solutions is provided. Chapter 13 is specifically dedicated to the problem of attenuating multiple unknown and time-varying vibrations. Two algorithms specifically developed for this problem will be presented and their performance and complexity will be compared with those of the basic algorithm presented in Chapter 12.

In the fifth part of the book we consider feedforward compensation of disturbances, which has to be used when the bandwidth of disturbances (vibrations) is such that the performance/robustness compromise cannot be conveniently satisfied by feedback alone. Chapter 14 examines the linear design, which has to be done from data (since the model of the disturbance is necessary). Chapter 15 provides adaptive solutions for infinite impulse response (IIR) feedforward compensation as well as experimental results illustrating the performance of such systems in various situations. Chapter 16 provides adaptive solutions for Youla–Kučera feedforward compensator configuration. Experimental comparison between the two configurations concludes the chapter.

Part six of the book contains five appendices. Appendix A is dedicated to the *generalized stability margin* and the *Vinnicombe distance* between two transfer functions: two very useful concepts in system identification in closed-loop operation and controller reduction. Appendix B details the numerically safe implementation of parameter adaptation algorithms in real-time. Appendix C details the derivation of an adaptation algorithm used in Chapter 13 for rejection of narrow-band disturbances. Appendix D details the derivation of explicit equations for the residual force or acceleration in the context of adaptive feedforward compensation. These equations allow the straightforward definition of the appropriate parameter adaptation algorithm. Finally Appendix E gives details and experimental evaluation of an *integral plus proportional* parameter adaptation algorithm (IP-PAA adaptation), which adds a “proportional” component to the classical “integral” parameter adaptation algorithms.

Pathways through the Book

For a course on the subject, the Chapters 1 to 9 have to be covered first followed, in no particular order, by Parts III, IV or V.

For experts in digital, robust and adaptive control, Chapters 3, 4, 5, 7, 8, and 9 can be skipped and again Parts III, IV and V can be read in any order.

An image of the applicability of the results can be easily obtained by reading Chapter 2 and the sections concerning experimental results in Chapters 10 to 16.

Figure 0.1 gives a view of the interdependence of the various chapters.

Acknowledgements

I would like first to thank M. Noé, who on one hand designed the bench tests and on the other hand pointed out the pertinent problems to be solved in active vibration control. The long, steady interaction between us was a major driving factor in our research on active vibration control.

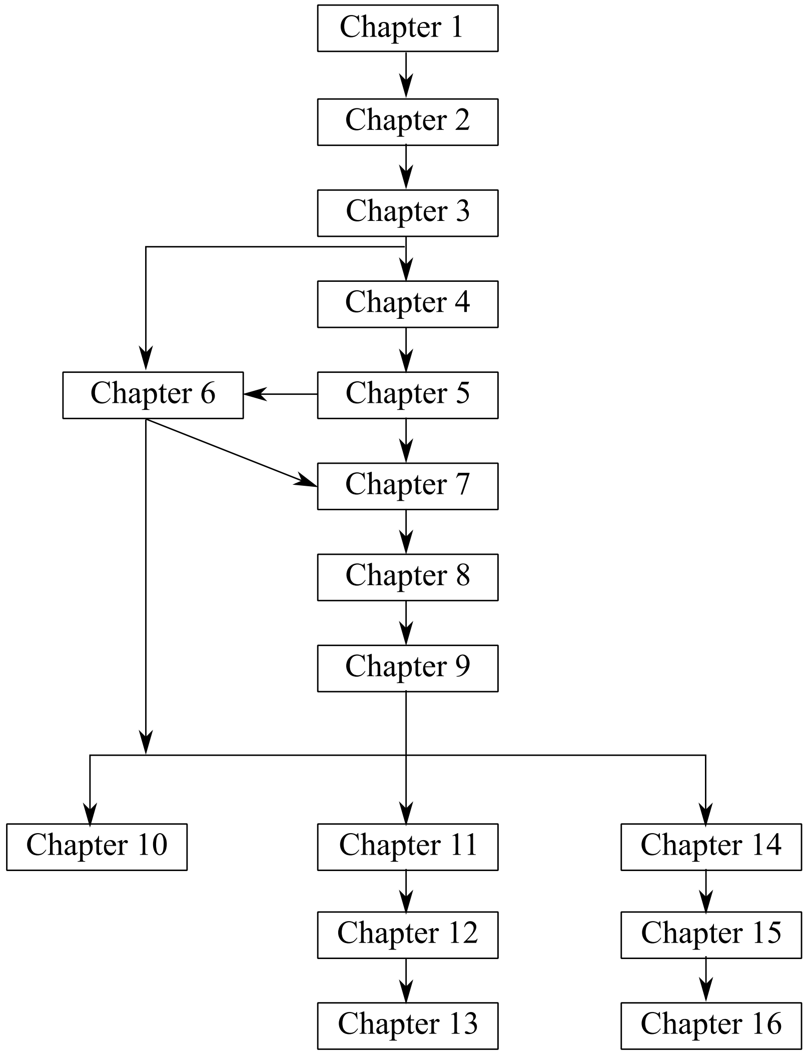

Fig. 0.1 Pathways through the book.

I would like to thank M. Alma, whose contributions to the field of active vibration control are reflected in the book.

I would like to thank D. Rey, G. Buche and A. Franco for their involvement in the research project and the technical support in operating the test benches.

Over the years, working in the area of active vibration control, I have had the privilege of interacting with a number of colleagues among whom I would like to mention: B.D.O. Anderson, S. Aranovski, F. Ben Amara, R.B. Bitmead, D. Bonvin, M. Bodson, R.A. de Callafon, X. Chen, L. Dugard, T. Hélie, P. Ioannou, C.R. Johnson, A. Karimi, J. Langer, F.L. Lewis, J.J. Martinez, G. Ruget, R. Serra, M.

Tomizuka, S. Valentinotti, Z. Wu. I would like to express my appreciation for their contributions.

The long term support of the Centre National de la Recherche Scientifique (CNRS) and of the GIPSA-LAB Grenoble (Institut National Polytechnique de Grenoble, Université Joseph Fourier, CNRS) is gratefully acknowledged.

I would also like to thank Oliver Jackson from Springer whose enthusiasm and professionalism has helped us to finalize this book.

Grenoble, France *Ioan D. Landau*

April 2016