Contents

Part I Introduction

1 Introduction to Interior Active Noise Control ................. 3
   1.1 Idea, Limit and Structure of Active Control Concepts .......... 3
   1.2 Remarks on Interior Noise and Active Control Approaches ...... 5
      1.2.1 Comments on the Interior Noise Problem .................. 5
      1.2.2 Comments on Active Control Approaches .................. 6
      1.2.3 A Qualitative Comparison of Active Control Approaches .... 7
   1.3 Examples for Engineering Applications of Interior ANC ....... 15
   1.4 Objective of Book ...................................... 17

Part II The Mechatronic Background of Feed-Forward Active Noise Control

2 Comments on Signals and Systems ................................ 25
   2.1 Comments on Signals ....................................... 25
      2.1.1 Classification ......................................... 26
      2.1.2 Characteristic Values and Functions ...................... 27
   2.2 Comments on Systems ....................................... 32
      2.2.1 Definitions ............................................. 32
      2.2.2 Transfer Behavior of LTI-Systems ....................... 32

3 Dynamics of Basic System ...................................... 35
   3.1 Basic Field Variables ...................................... 35
   3.2 Acoustic Field Equations ................................... 36
   3.3 Energy Density and Sound Intensity .......................... 39
   3.4 One-Dimensional Enclosed Sound Fields ...................... 41
      3.4.1 Free Vibrations in One-Dimensional Sound Fields ....... 41
      3.4.2 Forced Vibrations in One-Dimensional Sound Fields .... 43

4 Sensors for Active Noise Control ................................ 49
   4.1 Acoustical Sensing by Condenser Type Microphones ............ 50
## Contents

4.2 Sound Intensity Measurement ........................................ 52  
4.2.1 Functional Principle of Sound Intensity Probes .......... 52  
4.2.2 Errors in Sound Intensity Measurements ................. 54  
4.3 Structural Sensing by Accelerometers ....................... 58  

5 Actuators for Active Noise Control ................................. 61  
5.1 Electro-Dynamical Loudspeakers ............................. 61  
5.2 Electro-Dynamical Panel Speakers .......................... 65  

6 Active Control of Tonal and Broadband Noise .................... 71  
6.1 Mathematical Preparation ........................................ 72  
6.1.1 Hermitian Matrices ....................................... 72  
6.1.2 Quadratic Optimization ................................... 73  
6.1.3 Steepest-Decent Algorithm ................................ 74  
6.2 Terms and Structure of Feed-Forward Control Approaches ........ 76  
6.3 Review and Evaluation of Control Strategies ............... 77  
6.3.1 Description of Benchmark System and Close Form Solution 78  
6.3.2 Analysis of Specific Control Strategies ................. 80  
6.3.3 Comparison of Control Strategies ....................... 94  
6.4 Multi-channel Control of Tonal Noise ....................... 104  
6.4.1 Optimal Control of Tonal Noise ....................... 104  
6.4.2 Adaptive Control of Tonal Noise ....................... 107  
6.5 Active Control of Tonal Noise with Modified Cost Functions . 109  
6.5.1 Optimal Control Using a General Cost Function .......... 110  
6.5.2 Remote Sensor Control ............................... 110  
6.5.3 Parametric Controller Design .......................... 118  
6.6 Multi-channel Control of Stochastic Disturbances .......... 126  
6.6.1 Optimal Control of Stochastic Disturbances .......... 126  
6.6.2 Adaptive Control of Stochastic Disturbances ........ 128  
6.7 A Very Short Note on Adaptive Feedback Control .......... 144  

**Part III ANC-System Design: Theory**

7 ANC-System Design Tools ........................................... 149  
7.1 Numerical Analysis of Sound Fields ......................... 149  
7.1.1 A Short Overview on Numerical Methods ................. 149  
7.1.2 The Finite Element Method ............................. 151  
7.2 Inverse Noise Source Identification .......................... 155  
7.2.1 A Note on Source Identification Methods ............... 155  
7.2.2 The Inverse Finite Element Method .................... 157  
7.3 Initial Performance Estimation ............................ 163  
7.3.1 Coherence Analysis .................................... 164  
7.3.2 Transducer Placement Analysis ........................ 167  
7.3.3 Correlation Analysis ................................... 168  
7.3.4 Impulse Response Analysis ........................... 170  
7.3.5 A Short Comparison of Initial Performance Estimators 172  
7.4 Two Short Remarks on the Effect of Sampling Frequency .... 174
7.4.1 Attenuation of Aliasing ........................................... 174
7.4.2 Comments on Filter Delay ........................................... 174

8 ANC-System Design Methodology ........................................ 177
8.1 A Note on the Design Methodology for Mechatronic Systems .... 177
8.2 System Maturity Levels .............................................. 179
8.3 A Design Methodology for ANC-Systems ......................... 181
   8.3.1 ANC-System Design Tasks ..................................... 181
   8.3.2 ANC-System Design Steps ..................................... 182
   8.3.3 Matrix Model of the ANC-System Design Process ........... 184

Part IV ANC-System Design: Examples

9 Active Noise Control in a Semi-closed Interior ....................... 189
   9.1 Description of Problem and Requirements ...................... 189
      9.1.1 Requirements .............................................. 192
   9.2 Feasibility Study on ANC for the MA WA ........................ 192
      9.2.1 Noise Field Analysis for the MA WA ...................... 192
      9.2.2 Formulation of ANC-System Concept for the MA WA .... 195
      9.2.3 Proof of MA WA ANC-System Concept ..................... 196
   9.3 First Specification of Active Noise System .................... 201
      9.3.1 First Specification of Microphones ....................... 202
      9.3.2 First Specification of Actuators .......................... 203
      9.3.3 First Specification of Controller Software ............... 203
      9.3.4 Evaluation of First Specification ......................... 204
   9.4 Weight, Cost and Efficiency Study ............................... 206
      9.4.1 Actuator Design for ANC in the MA WA ................. 206
      9.4.2 Improvement of Adaptive Signal Processing ............. 208
      9.4.3 Optimization of Sensor and Actuator Locations .......... 213
   9.5 Sensitivity Study for ANC in MA WA ............................. 220
   9.6 Robust Control of Sound in the MA WA .......................... 220
      9.6.1 Design, Construction and Verification of Relevant Test Rig 221
      9.6.2 Determination and Modeling of Uncertainties .......... 225
      9.6.3 Review of the MA WA Robust Control Approach ........... 228
   9.7 Design Process Summary ......................................... 234

10 A Sound Intensity Probe with Active Free Field ..................... 237
   10.1 Feasibility Study on an Active Intensity Probe ............. 237
      10.1.1 Analysis of the Controlled Sound Field ............... 237
      10.1.2 Formulation of SIAF-System Concept ..................... 242
      10.1.3 Controller Design and Proof of SIAF-System Concept .... 242
   10.2 First Specification of an Active Intensity Probe ............ 246
      10.2.1 First Specification of System Hardware ................. 246
      10.2.2 Test of First SIAF-Specification ....................... 247
   10.3 Design Process Summary and Outlook ............................ 253
Adaptive Feed-Forward Control of Low Frequency Interior Noise
Kleutschkowski, Th.
2012, XXXVI, 330 p. 181 illus., 116 illus. in color., Hardcover