

Multichannel Signal Processing for Spatially Distributed Microphones

Dissertation

zur Erlangung des akademischen Grades

Doktor der Ingenieurwissenschaften

(Dr.-Ing.)

der Technischen Fakultät

der Christian-Albrechts-Universität zu Kiel

vorgelegt von

Sebastian Stenzel

Konstanz 2014

1. Berichterstatter: Prof. Dr.-Ing. Gerhard Schmidt
2. Berichterstatter: Prof. Dr.-Ing. Jürgen Freudenberger
Datum der mündlichen Prüfung: 29.04.2014

Konstanz, im Januar 2014
Sebastian Stenzel

Arbeiten über digitale Signalverarbeitung und Systemtheorie

Band 2

Sebastian Stenzel

**Multichannel Signal Processing for
Spatially Distributed Microphones**

Shaker Verlag
Aachen 2014

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Kiel, Univ., Diss., 2014

Copyright Shaker Verlag 2014

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-3053-2

ISSN 2197-7089

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: www.shaker.de • e-mail: info@shaker.de

Acknowledgments

First of all I would like to thank my supervisor Prof. Dr.-Ing. Jürgen Freudenberger for the possibility to conduct my Ph.D at the Institute for System Dynamics (ISD) of the University of Applied Sciences (HTWG) Konstanz, Germany. Working on my Ph.D at the HTWG became possible due to his effort. Most importantly I would like to thank him for all the support and advice he gave me within the last years. In our small research group he stimulated numbers of fruitful discussions and he gave me the opportunity for a research internship at the University of Kiel. Moreover I would like to thank my colleagues Jens Spinner, Uwe Kaiser, Stefan Hermanutz and Michael Blaich for the time in and outside the institute.

During the internship and visits at the University of Kiel, I felt warmly welcomed in the Digital Signal Processing and System Theory (DSS) group. In Kiel I had the possibility to work together with my supervisor Prof. Dr.-Ing. Gerhard Uwe Schmidt. I would like to thank him for the advice during the time in Kiel and also for the discussions in Konstanz and via Skype. His friendly and creative manner and the way he formed the DSS team impressed me. In Kiel I had the possibility to get in contact with further Ph.D students, researchers and research groups. Also beside my research activities I had a wonderful time in Kiel and for this I would like to thank Anne Theiß, Jochen Withopf and Roman Kreimeyer who inspired me to the weekly ‘Get Dirty’ bicycle tours along the river ‘Schwentine’. Furthermore I would like to thank all DSS team members (especially Christoph Norrenbrock and Christian Lüke) for the activities during my time in Kiel.

During the last steps of my thesis, I got in contact with Prof. Dr. ir. Simon Doclo and Dipl.-Ing. Toby Christian Lawin-Ore. I would like to thank them for the discussions in Oldenburg, Konstanz and also via Skype.

For proofreading this thesis I would like to thank Melanie Seiß. Furthermore thanks go to everyone who supported me during the time of my Ph.D project.

Contents

1	Introduction	1
1.1	Problem Statement	2
1.2	Structure of this Thesis	3
2	Optimal Signal Combining	5
2.1	The Signal Model	7
2.2	Narrow-band Beamforming in Room Acoustics: An Example	9
2.3	Matched Filtering	13
2.4	Max-SNR Beamformer	17
2.5	Minimum Variance Beamformer	21
2.5.1	On the Narrow-band Output SNR	22
2.5.2	Minimum Variance Distortion-less Response	23
2.5.3	Using Relative Transfer Functions	24
2.6	Parametric Multichannel Wiener Filter	26
2.6.1	The Multichannel Wiener Filter	28
2.6.2	Using an Explicit Reference Channel	29
2.7	Summary	30
3	Signal Combining for Distributed Microphone Arrays	33
3.1	The Acoustic Conditions	34
3.1.1	The Conference Scenario	34
3.1.2	The Car Environment	36
3.1.3	Discussion of the Measurements	39
3.2	Using Relative Transfer Functions with Distributed Microphones	41
3.2.1	Overall Transfer Function of the Reference Channel	41
3.2.2	Effects on the Broad-band Output SNR	42
3.2.3	Colorization of the Residual Noise	44
3.3	Minimum Variance Beamforming with Partial Equalization	46

3.4	Multichannel Wiener Filtering with Partial Equalization	52
3.4.1	Rank-1 Multichannel Wiener Filter	55
3.4.2	The multichannel Wiener filter for spatially uncorrelated noise	56
3.4.3	The multichannel Wiener filter for diffuse noise	58
3.5	Summary	59
4	Estimation of Second-Order Statistics and Implementation	61
4.1	Estimation of the Noise Power Spectral Density	64
4.1.1	Speech Presence Probability	64
4.1.2	Time-frequency Dependent Voice Activity Detection	66
4.1.3	Implementation of the PSD Estimation	67
4.2	Estimation of the Noise Correlation Matrix	72
4.2.1	Speech Presence Probability for Multichannel Signals	72
4.2.2	Multichannel Voice Activity Detection	75
4.2.3	Error Probabilities	75
4.2.4	Implementation of the Correlation Matrix Estimation	77
4.2.5	Evaluation of the Voice Activity Detection	80
4.3	The Generalized Sidelobe Canceler in Room Acoustics	82
4.3.1	An Equivalent Optimization Criterion for MV Beamformers	84
4.3.2	Reformulation of the Constrained Optimization Problem	85
4.3.3	Adaptive Implementation of the Noise Canceler	87
4.3.4	Blocking Matrix	89
4.3.5	Implementation of the GSC-Structure	91
4.4	Summary	92
5	Evaluation of the Algorithms	93
5.1	Simulation Environment	93
5.1.1	Parameter Setup	94
5.1.2	Objective Quality Measures	96
5.1.3	Instrumental Quality Measure: 3-Quest	97
5.2	Simulation Results: Car Environment	98
5.2.1	Objective Quality Results	99
5.2.2	Instrumental Quality Results	102
5.3	Simulation Results: Conference Scenario	104
5.3.1	Objective Quality Results	105
5.3.2	Instrumental Quality Results	107

5.4 Discussion	109
6 Conclusions	111
A Appendix to the Matrix Inversion Lemma	113
A.1 The Matrix Inversion Lemma	113
A.2 Decomposition of the Parametric Multichannel Wiener Filter	113
A.3 Iterative Calculation of the Inverse Noise Correlation Matrix	115
List of Acronyms	117
Bibliography	119
Kurzfassung	127
Ehrenwörtliche Erklärung	129