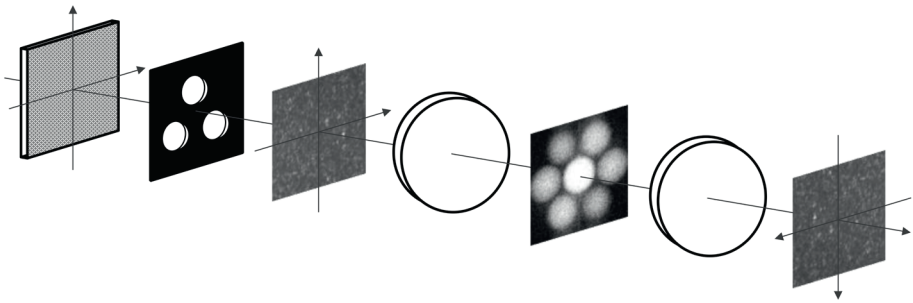
TECHNISCHE UNIVERSITÄT MÜNCHEN

REPORTS ON MEASUREMENT AND SENSOR SYSTEMS

Adjustable Aperture Multiplexing Technique in Electronic Speckle Pattern Interferometry

Min Lu



INSTITUTE FOR MEASUREMENT SYSTEMS AND SENSOR TECHNOLOGY

MST

Fakultät für Elektrotechnik und Informationstechnik
Lehrstuhl für Messsystem- und Sensortechnik

Adjustable Aperture Multiplexing Technique in Electronic Speckle Pattern Interferometry

Min Lu

Vollständiger Abdruck der von der Fakultät für
Elektrotechnik und Informationstechnik
der Technischen Universität München
zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs

genehmigten Dissertation.

Vorsitzender:		Prof. Dr.-Ing. Gerhard Rigoll
Prüfer der Dissertation:	1.	Prof. Dr.-Ing. habil. Dr. h.c. Alexander W. Koch
	2.	Prof. Félix José Salazar Bloise, Ph.D.

Die Dissertation wurde am 26.06.2018 bei der
Technischen Universität München eingereicht und durch die Fakultät für
Elektrotechnik und Informationstechnik am 26.11.2018 angenommen.

Reports on Measurement and Sensor Systems

Min Lu

Adjustable Aperture Multiplexing Technique in Electronic Speckle Pattern Interferometry

Shaker Verlag
Düren 2019

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.: München, Techn. Univ., Diss., 2019

Copyright Shaker Verlag 2019
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 978-3-8440-6673-9
ISSN 1617-6553

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren
Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9
Internet: www.shaker.de • e-mail: info@shaker.de

Contents

Abstract **i**

1 Introduction **1**
1.1 Background . . . 1
1.1.1 Historical development of speckle interferometry . . . 1
1.1.2 State of the art in spatial carrier phase-shifting technique . . . 3
1.2 Problem statement . . . 5
1.3 Purpose of the study . . . 6

2 Fundamentals of speckle interferometry **8**
2.1 Speckle effect . . . 9
2.2 Speckle size . . . 10
2.3 Speckle interferometry . . . 12
2.4 Shearography . . . 14
2.4.1 Optical configuration . . . 15
2.4.2 Shearing amount . . . 16
2.5 Working principle of shearography . . . 17
2.5.1 Sensitivity vector . . . 17
2.5.2 Measurement of out-of-plane displacement gradient . . . 20
2.5.3 Measurement of in-plane displacement gradient . . . 23

3 Phase retrieval **25**
3.1 Phase-shifting technique . . . 25
3.2 Classification of phase-shifting technique . . . 28
3.3 Temporal phase-shifting technique . . . 29
3.3.1 Working principle . . . 29
3.3.2 Means of temporal phase modulation . . . 33
3.4 Spatial phase-shifting technique . . . 36
3.4.1 Polarization component in multi-channel interferometer . . . 37

3.4.2 Pixelated phase mask in single-channel interferometer 38
3.4.3 Spatial light modulator 39
3.5 Spatial carrier phase-shifting technique 40
3.5.1 Fourier transform method 40
3.5.2 Means of spatial carrier introduction 44
3.6 Sine/cosine filtering process 47
3.7 Phase unwrapping process 51

4 Adjustable Aperture Multiplexing technique 54
4.1 Single-aperture arrangement 54
4.2 Double-aperture imaging system 57
4.3 Adjustable Aperture Multiplexing technique 61
4.3.1 Generation of adjustable carrier frequency 62
4.3.2 Aperture multiplexing construction 66
4.3.3 Phase retrieval using Fourier transform method 68
4.3.4 Optimization of carrier frequency and cut-off frequency 71

5 Out-of-plane displacement-slope measurement using AAM technique 77
5.1 Optical configuration 78
5.2 Adjustable virtual multiple-aperture mask 79
5.3 Phase extraction using spatial carrier frequency 84
5.4 Experimental results and discussions 87

6 In-plane rotation angular measurement using AAM technique 93
6.1 Modified in-plane ESPI system 94
6.2 Lateral displacement between object beams 96
6.3 Adjustable virtual double-aperture mask 98
6.4 Phase retrieval by spatial carrier frequency 102
6.5 In-plane angular measurement 103
6.6 Experimental results and discussion 107
6.7 Error analysis 112
6.7.1 Secant error 113
6.7.2 Tilt Uncertainty 116
6.7.3 Application example: eccentricity measurement 123

7 Full-field 3D displacement measurement using AAM technique 129
7.1 Optical arrangement 130
7.2 Working principle 132
7.3 Phase retrieval using spatial carrier frequencies 135

7.4 Experimental results and discussion 138
7.4.1 Rigid-body rotation 139
7.4.2 Deformation under central loading 142

8 Conclusion and further work **145**

Acknowledgements **154**

Symbols **156**

Abbreviations **163**

List of Figures **171**

List of Tables **172**

Bibliography **173**

Patents and Publications **192**

Supervised Works **194**