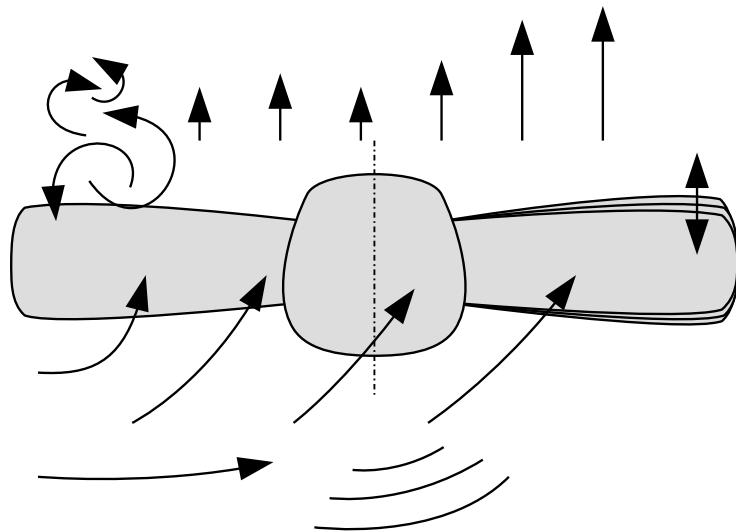


Till Heinemann

Axial Fans under the Influence of Various Uniform Ambient Flow Fields

Axialventilatoren unter dem
Einfluss verschiedener gleichförmiger
Strömungsfelder



BAND

Hrsg.: Prof. Dr.-Ing. E. Schlücker

34

Axial Fans under the Influence of Various Uniform Ambient Flow Fields

Axialventilatoren unter dem Einfluss verschiedener gleichförmiger Strömungsfelder

Der Technischen Fakultät
der Friedrich-Alexander-Universität
Erlangen-Nürnberg

zur
Erlangung des Doktorgrades Dr.-Ing.

vorgelegt von

Till Heinemann
aus Bochum

Als Dissertation genehmigt
von der Technischen Fakultät
der Friedrich-Alexander-Universität Erlangen-Nürnberg

Tag der mündlichen Prüfung: 28.11.2017

Vorsitzender des Promotionsorgans: Prof. Dr.-Ing. Reinhard Lerch

Gutachter: Prof. Dr.-Ing. Stefan Becker
Prof. Alessandro Corsini, PhD

Schriftenreihe des Lehrstuhls für Prozessmaschinen und
Anlagentechnik

Band 34

Till Heinemann

**Axial Fans under the Influence
of Various Uniform Ambient Flow Fields**

Axialventilatoren unter dem Einfluss verschiedener
gleichförmiger Strömungsfelder

D 29 (Diss. Universität Erlangen-Nürnberg)

Shaker Verlag
Aachen 2018

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.: Erlangen-Nürnberg, Univ., Diss., 2017

Copyright Shaker Verlag 2018

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 978-3-8440-5767-6

ISSN 1614-3906

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

Contents

Abstract	xiii
Kurzfassung	xv
1. Introduction	1
1.1. State of the Art and Motivation	1
1.1.1. Air cooled condensers	1
1.1.2. Adverse effects due to wind and recirculation	3
1.1.3. Counter measures to adverse wind influence	9
1.2. Aims and Objectives	12
1.3. Methodology and Structure	14
2. Fan Aerodynamics and Aeroacoustics	19
2.1. Governing Equations in Fluid Dynamics	19
2.2. Computational Fluid Dynamics	24
2.2.1. Turbulence modeling	24
2.2.2. Discretization	26
2.3. Fan Aerodynamics	27
2.3.1. Euler equation of turbomachinery	27
2.3.2. Integral fan properties	31
2.3.3. Fan blade aerodynamics	35
2.4. Similitude and Characteristic Fan Numbers	40
2.5. Ambient Flow Field at the Fan Inlet	46
2.5.1. Kinematics	47
2.5.2. Existing models and findings	50
2.5.3. Idealized kinematic crossflow effects	55
2.5.4. Summary and Discussion	62
2.6. Aeroacoustic Basics	63
2.6.1. Sound	63
2.6.2. Ffowcs Williams and Hawkings Method	65
2.7. Fan Noise	68
2.8. Blade Sweep and Skew	70
3. Experimental Setup	75
3.1. Measuring Object and Configurations	75
3.1.1. Operating configurations	76
3.1.2. Comparison of test fans with upscale target application fan	77

Contents

3.2. Acoustic Standard Fan Test Rig	79
3.3. Wind Tunnel Fan Test Rig	81
3.3.1. Estimation of uncertainty	87
3.4. Laser Doppler Anemometry: Experimental Setup	88
3.5. Laser Scanning Vibrometry	92
3.6. Aeroacoustic Wind Tunnel	95
4. Numerical Setup	99
4.1. Simulation Model	99
4.2. Simulation Settings and Mesh	101
5. Assessment of Kiel Probe Array Performance and Applicability	105
5.1. Yaw sensitivity of Kiel probe array	105
5.2. Applicability to Fan Test Rig Measurements	108
5.2.1. Theoretic estimation	108
5.2.2. LDA measurements of the effective tilt angles	109
5.2.3. Comparison of mass flow integration and area integration	112
5.2.4. Summary	117
6. Reference Properties of Examined Axial Fans	119
6.1. Fan Pressure and Efficiency	119
6.1.1. Fan performance under different installation conditions	119
6.1.2. Influence of duct and flow straightener	123
6.1.3. Comparison of test rigs and simulation	126
6.1.4. Summary	127
6.2. Flow Field	128
6.2.1. Measured velocity distributions at fan outlet in duct section	128
6.2.2. Energy and pressure at fan outlet in duct section	133
6.2.3. Fan flow field from CFD	140
6.2.4. Summary	145
6.3. Fan Blade Vibration	145
6.3.1. Numerical modal analysis	146
6.3.2. Vibration from Laser Scanning Velocimetry	153
6.3.3. Summary	157
6.4. Fan Acoustics	161
6.4.1. Microphone measurements	161
6.4.2. Estimation of Sound radiated from surface vibration data	166
6.4.3. Numerical aeroacoustics from CFD data	170
6.4.4. Summary	172
7. Influence of Ambient Flow Fields	175
7.1. Fan Pressure and Efficiency influenced by Uniform Ambient Flow Field	175
7.1.1. Fan inlet affected by flow field	175
7.1.2. Fan outlet affected by flow field	184

7.2.	Flow Field influenced by Uniform Ambient Flow Field at Inlet	186
7.2.1.	Velocity distribution at fan outlet from LDA	186
7.2.2.	Flow Field in URANS Simulations	195
7.2.3.	Summary	198
7.3.	Fan Blade Vibration Influenced by Inlet cross-flow	204
7.3.1.	Spectral decomposition of integral fan blade vibration	204
7.3.2.	Spatial resolution of wind influence on blade vibration	206
7.4.	Fan Acoustics Influenced by Inlet cross-flow	212
7.4.1.	Microphone measurements	212
7.4.2.	Estimation of sound radiated from surface vibration data	219
7.4.3.	Numerical aeroacoustics from CFD data	222
7.4.4.	Summary	224
8.	Effect of Inlet Modifications to Ambient Flow Sensitivity	227
8.1.	Inlet Extension Geometries	227
8.2.	Influence on Characteristic Fan Curves	229
9.	Summary and Outlook	235
9.1.	Summary of the Research Activities and Most Important Results	235
9.2.	Outlook to Future Investigations	240
A.	Appendix	243
A.1.	Fundamental Mathematics	243
A.1.1.	Conventions of notation	243
A.1.2.	Errors and uncertainty	245
A.1.3.	Spectral analysis	247
A.2.	Mass flow averaging and area averaging	249
A.3.	Computation of flow rate from multiple nozzles	251
A.4.	Applicability of FWH on blade surface vibration data	252
A.5.	Supplementary Figures	254
A.5.1.	Diagrams	254
A.5.2.	Wind Tunnel Fan Test Rig Images	255
A.6.	Supplementary Results	260
A.6.1.	Uncertainty Computation	260
A.6.2.	Natural frequency computation	261
A.6.3.	Blade vibration measurements at rotation rate	265
A.6.4.	Flow field	267
A.6.5.	Mesh independence studies	269
A.6.6.	Acoustic Test Rig Comparison	271