On the Flow Induced Tip Clearance Noise in Axial Fans

DISSERTATION

zur Erlangung des Grades eines Doktors

der Ingenieurwissenschaften

vorgelegt von

Dipl.-Ing. Tao Zhu

geb. am 02.01.1984 in Peking, China

eingereicht bei der
Naturwissenschaftlich-Technischen Fakultät
der Universität Siegen

Referent: Prof. Dr.-Ing. Thomas Carolus
Korreferent: Prof. Dr.-Ing. Peter F. Pelz

Tag der mündlichen Prüfung:
26. August 2016

Berichte aus der Strömungstechnik

Tao Zhu

On the Flow Induced Tip Clearance Noise in Axial Fans

Shaker Verlag
Aachen 2016

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.: Siegen, Univ., Diss., 2016

Printed in Germany.

ISBN 978-3-8440-4802-5
ISSN 0945-2230

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

Kurzfassung

Bei Axialventilatoren hängen die aerodynamische Leistung, der Wirkungsgrad und die Schallemission unter anderem von der Größe des Spalts zwischen Schaufelkopf und Gehäuse ab. Ziel der Arbeit ist eine detaillierte Untersuchung der Kopfspaltströmung bei einem generischen Niederdruckaxialventilator ohne Nachleitrad mit experimentellen und numerischen Simulationsmethoden. Zwei besondere Schwerpunkte sind dabei die Klärung des Mechanismus, der zur Schallentstehung aufgrund der Kopfspaltströmung führt, sowie die Suche nach konstruktiven Geräuschminderungsmaßnahmen.

Experimentell werden die üblichen aerodynamischen und akustischen Kennlinien des Ventilators ermittelt sowie punktweise strömungsinduzierte Oberflächenwechseldrücke auf den Schaufeloberflächen und den schaufelnahen Gehäusebereichen mittels Miniaturdrucksensoren gemessen. Das komplette Stromfeld im Ventilator, insbesondere auch im Bereich des Kopfspalts, wird numerisch mit stationären und instationären Navier-Stokes-Verfahren sowie mit der Lattice-Boltzmann Methode simuliert. Aus den instationären Navier-Stokes-Stromfelddaten wird der Fernfeldschall mit dem Verfahren von Ffwocs Williams und Hawkings berechnet, die Lattice-Boltzmann Methode liefert das akustische Fernfeld unmittelbar. Vergleichend werden jeweils zwei unterschiedlich große Kopfspalte betrachtet.

Experimente und Simulationen bestätigen die bekannten negativen Auswirkungen einer Vergrößerung des Kopfspalts auf die aerodynamischen und akustischen Eigenschaften eines Axialventilators. Im Detail zeigt sich, dass ein großer Kopfspalt betriebspunktabhängig die Schallemission breitbandig sowie schmalbandig in Frequenzbereichen, die nicht mit der Blattpassierfrequenz zusammenfallen, erhöht. Die Interaktion des komplexen Kopfspaltwirbelsystems mit Nachbarschaufeln erweist sich als Ursache für den kopfspaltverursachten Schall. Das System der Kopfspaltwirbel ist instationär, teilweise zerfällt es in kleine turbulente Wirbelstrukturen, was den Einfluss des Kopfspalts auf den Breitbandschall erklärt. Besonders bei Teillast des Ventilators lassen sich aber auch umfänglich kohärente Wirbelstrukturen nachweisen, die für die schmalbandigen Erhöhungen verantwortlich sind. Die Lattice-Boltzmann Methode erwies sich als besonders geeignetes Werkzeug zur Vorhersage der Schallemission des Ventilators und zur Detektion der Schallentstehungsmechanismen.

Basierend auf den gewonnenen Erkenntnissen wird eine neuartige Gehäusegestaltung vorgeschlagen, mit der sich die Wirbelstrukturen im Kopfspaltbereich der Rotorschaufeln deutlich unterdrücken lassen. Experimente zeigen, dass damit auch das Kopfspaltgeräusch signifikant reduziert werden kann.

Abstract

The effect of unavoidable tip clearance in axial fans is significant since a large clearance does not only degrade the overall aerodynamic performance, but it also increases the sound radiation into the far-field dramatically. The overall objective of this thesis is hence the detailed investigation of the tip clearance flow and subsequent of the sound generating mechanism, which can eventually pave the way for new and innovative low-noise fan designs.

In this study, comprehensive experimental and numerical investigations are conducted based on an impeller-only low pressure axial test fan in two tip clearance variations. Besides the overall aerodynamic and acoustic tests, the more detailed measurements of surface pressure fluctuations in the blade tip region show the footprints of the complex tip clearance flow. The underlying complete three-dimensional tip clearance flow field and its correlation with the acoustic field, however, can only be understood by carrying out advanced numerical simulations. Hence, various steady and unsteady Navier-Stokes based approaches with subsequent acoustic model as well as the Lattice-Boltzmann method are applied.

Both experimental results and numerical predictions confirm the aforementioned well-known effects of an increase in tip clearance. The effect of a large tip clearance on the sound pressure spectrum is twofold: (i) an increase in the broadband floor and, (ii) specifically at lower volume flow rates, the appearance of pronounced narrowband humps with center frequencies that are linked to the rotational speed of the impeller but that are not integer multiples of the blade-passing frequency. It is found that they result from the interactions of the impeller blades in the tip region with (i) the highly turbulent small vortex structures decayed from the tip clearance vortices during extending through the local blade passage and (ii) the global circumferentially coherent vortex structures – a superposition of circumferential modes of different mode orders, which rotate slower than the impeller blades.

The Lattice-Boltzmann method (LBM) also proved to be a suitable tool for the aeroacoustic prediction and investigation of the fan noise generating mechanism with a feasible computational effort.

Based on these findings, a novel casing treatment is designed that is able to substantially suppress tip clearance vortex structures and hence significantly reduce the tip clearance noise.

Acknowledgements

This thesis was written during my time as a research assistant at the Institute for Fluid- and Thermodynamics (IFT) at the University of Siegen. First and foremost I would like to express my sincerest gratitude to my advisor Prof. Dr.-Ing. Thomas Carolus, not only for his continuous support of my Ph.D. study and related research, but also for his very thoughtful personal guidance. With his dedication he has built a great institute promoting curiosity, creativity and ethics, but also with a nice familiar atmosphere. That's why I prefer to call him as my "doctor FATHER" rather than only my advisor! At the same time, I would like to acknowledge my appreciation to Prof. Stéphane Moreau, Ph.D., for the opportunity to spend a five weeks research stay in his group at the Université de Sherbrooke and for his interest, guidance and hospitality. Furthermore, I am truly thankful to Marlène Sanjosé, Ph.D., for the wonderful time working together when I was in Sherbrooke and during her research stay in Siegen.

In additional, I am very grateful to Prof. Dr.-Ing. Peter F. Pelz from Technische Universität Darmstadt as my 2nd reviewer, for the inspirations and the constructive discussions.

I am extremely thankful to all the colleagues in IFT, in particular, the "old guys": Dr.-Ing. Julian Winkler, Dr.-Ing. Michael Kohlhaas, Dr.-Ing. Konrad Bamberger, Dr.-Ing. Tom Gerhard, Dr.-Ing. Christoph Moisel and Dr.-Ing. Sebastian Knirsch, and the "new generation": M. Sc. Kevin Volkmer, M. Sc. Carolin Feldmann, Dipl.-Ing. Nicholas Kaufmann, M. Sc. Farhan Manegar and M. Sc. Leonard Schorle, for the consistent helpfulness and the unforgettable time together, in the office, the laboratory, the daily 10 o' clock coffee break and during the conferences. Special thanks to Dr.-Ing. Ralf Starzmann, who guided my Diplom-thesis as I was still a student and introduced me to the IFT-group, and to Dr.-Ing. Michael Sturm for the amazing 5-years time in the same office and the great teamwork. Of course I will never forget our wonderful secretary Christine Krause, the "IFT-mommy", and our irreplaceable laboratory engineer Dipl.-Ing. Bernd Homrighausen for their unconditional support. I would like also thank the alumni Dr.-Ing. Hauke Reese, Dr.-Ing. Marc Schneider and Dr.-Ing. Daniel Wolfram for the advice and cooperation by my research projects. Special thanks also to M. Sc. Dominic Lallier-Daniels for all his assistance during my stay in Sherbrooke and the fruitful research cooperation. Furthermore thanks to all student assistants and graduates, who have accompanied and supported me throughout my research.

I am very grateful to all employees of the workshop of the Faculty of Technology and the HorUS cluster at University of Siegen, for their fine work, valuable advice and assistance.

This study was partly funded by the German Ministry for Economic Affairs and Energy (BMWi) via the German Federation of Industrial Research Associations (AiF) and the Research Association for Air and Drying Technology (FLT) within the scope of the IGF projects 16773 N/2 and 18185 N/1.

Last but not least, I would like to deeply thank my parents Jingjian and Huating, my wonderful wife Yan and our lovely daughter Zihan, for their unconditional love and support.

To my parents,
Jingjian and Huating,
and to my wife,
Yan,
and our daughter,
Zihan

Contents