

On the Flow Induced Tip Clearance Noise in Axial Fans

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zur Erlangung des Grades eines Doktors
der Ingenieurwissenschaften

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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 Blatt-passierfrequenz 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.

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

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