Poznań University of Technology

Doctoral Thesis

Method for direct noise analysis of transonic axial compressor blade

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy. Engineer.

in the

Faculty of Work Machines and Transportation
Chair of Thermal Engineering

July 22, 2018

Declaration of Authorship

I, MSc. Eng. Jędrzej Mosiężny, declare that this thesis titled, 'Method for direct noise analysis of transonic axial compressor blade' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

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Abstract

This thesis proposes a method of assessing flow generated noise in transonic flows by direct formulation.

First a steady state Reynolds Averaged Navier-Stokes analysis of NASA R67 transonic axial compressor is performed as a validation study of the mesh and numerical setup. The result of the steady state analysis is then used as an initialization for transient DDES analysis performed on high quality, 11 million cells hexagonal mesh. The transient analysis covers 0.05s of physical flow time, which corresponds to about 800 revolutions of the rotor. Both steady state and transient simulations are performed on PL-Grid HPC infrastructure.

Transient results are analyzed with an in-house build program. The program uses information about static pressure, transient particle velocity and vorticity from each timestep. This data is then postprocessed into sound pressure levels, sound frequency and effective sound power level.

Information on generation of sound phenomena occurring in the blade passage are gathered from direct formulation and may be used as a validation case for FW-H or other computational aeroacoustic analogies dealing with flows in transonic regimes in rotating machinery.

Acknowledgements

In this place I would like to thank the Chair of Thermal Engineering of Poznań University of Technology, with special recognition to MSc. Eng. Bartosz Ziegler and PhD Eng. Przemysław Grzymisławski for thorough scientific and personal support during this project.

A big recognition goes to the owners and maintainers of the PLGRID - Polish HPC infrastructure, especially team in HPC Cyfronet center in AGH University of Science and Technology in Kraków. Being able to use the state of the art HPC clusters for analyses made this project possible.

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Abbreviations

CAA	**C**omputional **A**ero **A**coustics
CFD	**C**omputional **F**luid **D**ynamics
DDES	**D**elayed **D**etached **E**ddy **S**imulation
DES	**D**etached **E**ddy **S**imulation
HPC	**H**ight **P**ower **C**omputing
LES	**L**arge **E**ddy **S**imulation
N-S	**N**avier **S**tokes
SRS	**S**cale **R**resolving **S**imulation

Physical Constants

Speed of Light $\quad c \quad = \quad 2.997\ 924\ 58 \times 10^{8}\ \mathrm{ms}^{-\mathrm{S}}$ (exact)

Symbols

a	distance	m
P	power	W (Js^{-1})
ω	angular frequency	$rads^{-1}$

To my wife. For limitless patience...

Chapter 1

Introduction

1.1 Main Section 1

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Chapter 2

Current research on Computational Aeroacoustics

2.1 Main Section 1

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Chapter 3

Approach and direct formulation of noise analysis

3.1 Basic conservation equations in CFD

3.1.1 Momentum equations

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3.1.2 Continuity Equations

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3.1.3 Energy equation

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3.2 Resolving turbulence

3.2.1 RANS formulation of turbulent flow

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3.2.2 DDES Formulation of turbulence

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Chapter 4

Test case

4.1 NASA Rotor 67 transonic axial compressor

The test specimen for given analysis is a NASA Rotor 67 transonic axial compressor. Originating as a first stage of two stage fan for evaluation of design procedures, validation of experimental facilities as well as meshing and CFD tools. Both stages were used in a multitude of studies for aerodynamics, geometry optimisation, noise analyses and structural analyses. Full design procedure can be found in references [2] and [3]. The CFD analysis and further post processing of the pressure signals shall be performed on a single passage of a first stage rotor of the compressor. The setup for the calculations (apart from the single passage constraint) is relevant do case described in [4], which was the main source for geometry and flowfield data.

Basic figures of the given rotor are, design pressure ratio of 1.63 at massflow of 33.25 kg/sec. The design rotational speed is 16 043 rpm, which yields a tip speed of 429 m/s and an inlet tip relative Mach number of 1.38. The rotor has 22 blades and an aspect ratio of 1.56 (based on average span/root axial chord). The inlet and exit tip diameters are 514 and 485 mm, respectively, and the inlet and exit hub/tip radius ratios are 0.375 and 0.478, respectively. A fillet radius of 1.78 mm is used at the airfoil-hub juncture. The square root of the mean square of the airfoil surface finish is 0.8 μm or better, the airfoil surface tolerance is $\pm$ 0.04 mm, and the running tip clearance is approximately 1.0 mm [4]. Surface roughness and some of the geometrical features are omitted during the preparation of the geometry and CFD mesh for reasons described in sections 4.2 and 4.3.

4.1.1 Efficiency figures

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4.1.2 LDA Validation results

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4.2 3D geometry preparation

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4.3 Structural Mesh

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4.4 Case preprocessing

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4.4.1 Boundary conditions

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4.4.2 Numerical scheme

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Chapter 5

RANS Analysis

5.1 Main Section 1

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Chapter 6

DDES Analysis

6.1 Main Section 1

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Chapter 7

Results of flow field noise analysis

7.1 Main Section 1

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Chapter 8

Conclusions & Further work

8.1 Main Section 1

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Appendix A

Code for direct formulation of noise analysis

Write your Appendix content here.

Appendix B

Code for discrete Fourier analysis

Write your Appendix content here. [5] [6] [7] [1] [8] [2] [3] [4]

Bibliography

[1] D. L. Hawkings J. E. Ffowcs Williams. Sound generation by turbulence and surfaces in arbitrary motion. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 264(1151):321–342, May 1969. URL `http://www.jstor.org/stable/73790`.

[2] W. Stevans W. S. Cunnan and D. C. Urasek. Design and performance of a 427-meter-per-second-tip-speed two stage fan having a 2.40 pressure ratio. *NASA Technical Paper*, (TP-1314), October 1978.

[3] W. T. Gorrel D. C. Urasek and W. S. Cunnan. Performance of a two-stage fan having a low-aspect-ratio, first-stage rotor blading. *NASA Technical Paper*, (TP-1493), August 1979.

[4] M. D. Hathaway A. J. Strazisar, J. R. Wood and Kenneth L. Suder. Laser anemometer measurements in a transonic axial-flow fan rotor. *NASA Technical Paper*, (TP-2897), November 1989.

[5] M. J. Lighthill. On sound generated aerodynamically i. general theory. *Proceedings of the Royal Society. Series A, Mathematical, Physical and Engineering Sciences*, 211 (1107):564–587, March 1952. URL `http://rspa.royalsocietypublishing.org/content/211/1107/564`.

[6] M. J. Lighthill. On sound generated aerodynamically ii. turbulence as a source of sound. *Proceedings of the Royal Society. Series A, Mathematical, Physical and Engineering Sciences*, 222(1148):1–32, March 1954. URL `http://rspa.royalsocietypublishing.org/content/222/1148/1`.

[7] N. Curle. The influence of solid boundaries upon aerodynamic sound. *Proceedings of the Royal Society. Series A, Mathematical, Physical and Engineering Sciences*, 231(1187):505–514, September 1955. URL `http://rspa.royalsocietypublishing.org/content/231/1187/505`.

[8] J. S. David C. Janetzke J. E. Crouse and R. E. Schwirian. A computer program for composing blading from simulated circular-arc elements on conical surfaces. *NASA Technical Note*, (TN D-5437), September 1969.