POZNAŃ UNIVERSITY OF TECHNOLOGY

DOCTORAL THESIS

Method for direct noise analysis of transonic axial compressor blade

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for the degree of Doctor of Philosophy. Engineer.

in the

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Chair of Thermal Engineering

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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.

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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

Contents

List of Figures

List of Tables

Abbreviations

CAA	Computional Aero Acoustics
CFD	Computional Fluid Dynamics
DDES	Delayed Detached Eddy Simulation
DES	Detached Eddy Simulation
HPC	Hight Power Computing
LES	Large Eddy Simulation
N-S	Navier Stokes
SRS	Scale Rresolving Simulation

Physical Constants

Speed of Light $\quad c \quad = \quad 2.997\ 924\ 58 \times 10^8\ \mathrm{ms^{-S}}$ (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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3.2.3   DDES Formulation of turbulence

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3.3 Direct formulation of noise signal

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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 (R67) 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

4.1.2 LDA Validation results

4.2 3D geometry preparation

Geometry was prepared in Ansys ICEM 14.5 meshing software. Creating the geometry directly in the meshing software reduces the risk of creating flaws in the geometry, due to file translations. Mesh is created in millimeters.

The R67 blade coordinates for rotor and stator on both stages is given in references [2] and [3] and provide the blade elements in a Multiple-Circular-Arc fashion. In such approach the design blade elements lie on conical surfaces which approximate the actual stream flow surfaces. A blade-element-layout method is developed which preserves the constant-angle change characteristic of the circular-arc profile. More specifically, the mean camber line and the suction and pressure surface lines of a blade element are lines with a constant rate of angle change with path distance on a specified conical surface [5]. Although relatively comfortable for design purposes, such approach requires implementing a macro or script to desired CAD tool for creating the blade elements or transforming the MCA blade to Cartesian or cylindrical coordinates. Reference [5] provides an extended definition of MCA blade description as well as Fortran code for generating blade cross-section and geometric properties of the blade. Source [4] provides a list of coordinates for 14 profiles of the 1st stage rotor blade suction and pressure side, as well as coordinates for hub and casing int the meridional plane. These coordinates were used to create the geometry of the single passage of the subject blade. Coordinates are also available in Appendix C and project Github repository [6].

Geometry alignment is presented on figure 4.1. The coordinate system is a standard right-hand Cartesian CS. Rotation axis is set to Z-axis with flow in positive Z direction. The compressor rotation is set as in right-hand rule, the compressor rotates in clockwise direction when facing the blade leading edge. $Z = 0$ coordinate is defined by point number 1 on 1st blade design surface (see Appendix C for details).

Hub and casing flow path were created by importing formatted point data as a b-spline curve, followed by extrusion the curve to surface by rotating it by ±60°. Blade surfaces cylindrical coordinates were transformed to Cartesian coordinates using simple trigonometric calculations and imported as set of splines. Suction and pressure surface of the blade were created by lofting the surface along the imported splines. Leading and trailing edge radii were created in a similar manner with use of edge radius and edge tangency points given in [4]. Tip gap of the blade was created by offsetting the casing surface by

FIGURE 4.1: Global coordinate system for geometry

1.016 mm in the normal direction towards the rotation axis and creating a section line between blade surfaces and the offset surface.

Due to the estimated mesh cell count, only one blade passage is created, therefore a set of periodic surfaces must be defined. ICEM software is capable of creating a midline as an average of coordinates of two given lines. A midline was created for every design profile and was manually extended beyond the blade leading and trailing edge. Midlines were lofted to create a midsurface which was later on copied with rotation by $\pm 0.5 \cdot \frac{360°}{22}$ to create two identical periodic surfaces.

Aforementioned midlines were also rotated along Z-axis to create control surfaces for mesh stabilization and data acquisition down the process.

Reference [4] provides coordinates of hub and casing for the full experiment, however only a rotating part of the experimental rotor setup will be used. Two surfaces normal to Z direction at coordinates Z = -13.74 and Z = 93.65 are placed as inlet and outlet boundary conditions. Geometry was finished by necessary extrusions, trimming and other finishing operations to ensure high quality surface for meshing. Usually, the geometry must be watertight to ensure proper meshing process, however ICEM as patch-independent meshing software does not require that.

Physical experiment test compressor has a 1.78 mm fillet at airfoil-hub juncture. This feature was omitted as it would unnecessarily complicate the meshing process and increase the cell count.

Such approach allowed for creating a geometry for single blade passage with centered blade of 1st stage rotor of the test compressor (Fig 4.2).

FIGURE 4.2: Final single passage geometry

4.3 Meshing approach

Following requisites are posed to the mesh for the discussed case:

- Possibly low number of elements fulfilling the mesh sizing requirements stated in chapter 3.3,

- Mesh should be a fully structural mesh including the tip gap,

- The periodic boundary mesh must be identical/conforming for both boundaries,

- The mesh must have high quality metrics in terms of cell orthogonality and skew as defined by equations 4.1 & 4.2 respectively.

$$6^2 - 5 = 36 - 5 = 31 \tag{4.1}$$

$$6^2 - 5 = 36 - 5 = 31 \tag{4.2}$$

One of the initial mesh concepts was an unstructured mesh with triangular surface mesh extruded to prism boundary layer and mostly isotropic tetrahedra in the volume. This approach was quickly rejected for bad quality elements near the airfoil/hub junction and tip gap, as well as element count in range of 4.5 million cells for sizing relevant for RANS analysis. This approach was quickly dropped.

A non-trivial topology with fully conforming periodic boundaries was introduced (fig 4.3). This topology fulfills all the prerequisites stated apart from possibility to mesh a

FIGURE 4.3: Mesh topology with conforming periodic boundaries

structural tip gap. Such approach makes it impossible from topological standpoint to place a structural mesh in this area. A RANS sufficient mesh without tip gap area (blade was extended to the casing surface) was created. The cell count for this mesh is below 0.5 million cells with better skewness and orthogonal quality. This mesh was utilized for numerical setup and data acquisition testing as it was faster to converge.

Final topology was a standard h-grid topology for airfoil meshing. Although it is impossible to create a conforming periodic interface with such mesh, it is possible to create a fully structured tip gap.

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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6.2   Main Section 2

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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. [7] [8] [9] [1] [5] [2] [3] [4]

Appendix C

Blade design surface coordinates

Write your Appendix content here. [7] [8] [9] [1] [5] [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] 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.

[6] J. Mosiezny. Github repository for nasa r67 input data and noise analysis. 2018. URL https://github.com/JedrzejMosiezny/R67-data-analysis.

[7] 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.

[8] 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.

[9] 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`.