Strömungstechnik

Jan Philipp Heners

A Lanczos-filtered Harmonic Balance Method for Aeroelastic Applications of Turbomachinery Resolving Unsteady Turbulence Effects

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DECLARATION OF AUTHORSHIP

I declare that this research effort has been composed by myself and that the work has not been submitted for any other degree or professional qualification. I confirm that the work submitted is my own. The contribution of other authors to this work has been explicitly indicated below. I confirm that appropriate credit has been given within this thesis where reference has been made to the work of others.

The work presented in Sections 2.3, 2.4 and 5.1 was previously presented at the 15th International Symposium on Unsteady Aerodynamics, Aeroacoustics and Aeroelasticity of Turbomachines (ISUAAAT 15) and published in the ASME Journal of Turbomachinery as "*Investigation of the Impact of Unsteady Turbulence Effects on the Aeroelastic Analysis of a Low-Pressure Turbine Rotor Blade*" by **Jan Ph. Heners** (the author), **Prof. Dr. Damian Vogt** (1st supervisor), Dr. Christian Frey, and Dr. Graham Ashcroft. It has therefore been subject to the independent review process of the ASME Journal of Turbomachinery.

The work presented in Chapter 3 was previously published in the Proceedings of the ASME Turbo Expo 2020 as "*Prediction of the Unsteady Transition Behavior in Low Pressure Turbine Flows Using Time and Frequency Domain Methods*" by **Jan Ph. Heners** (the author), Dr. Christoph Müller-Schindewolffs, **Prof.**

Dr. Damian Vogt (1st supervisor), and Frederik Blum. It has therefore been subject to the independent review process of the ASME Turbo Expo.

The work presented in Chapter 4 was previously published in the Proceedings of the 14th European Conference on Turbomachinery Fluid Dynamics & Thermodynamics (ETC 14). In addition to that, an extended version of the conference paper was published in the International Journal of Turbomachinery, Propulsion and Power. Both were published under the title "*Prediction of Transient Pressure Fluctuations within a Low Pressure Turbine Cascade Using a Lanczos-Filtered Harmonic Balance Method*" by **Jan Ph. Heners** (the author), Dr. Stephan Stotz, Annette Krosse, Detlef Korte, Maximilian Beck, and **Prof. Dr. Damian Vogt** (1st supervisor) and have therefore been subject to the independent review process of the European Turbomachinery Society.

The work presented in Setions 6.3 and 6.4 was previously presented at the ASME Turbo Expo 2022 and published in the ASME Journal of Turbomachinery under the title "*Evaluating the Aerodynamic Damping at Shock Wave Boundary Layer Interacting Flow Conditions with Harmonic Balance*" by **Jan Ph. Heners** (the author), Dr. Christian Frey, and Dr. Björn Grüber. It has therefore been subject to the independent review process of the ASME Turbo Expo and the ASME Journal of Turbomachinery.

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ABSTRACT

This research thesis discusses the impact of unsteady turbulence effects on the numerical prediction of aerodynamic excitation mechanisms in turbomachinery flows. The limitations of existing solver structures based on a formulation in the frequency domain - the Harmonic Balance method, that is - promises to consider turbulence in an unsteady framework. Existing limitations to this are assessed and a solution approach to alleviate the identified sources of numerical instabilities is identified by the application of a Lanczos-type filter method.

After proper implementation and validation, the Harmonic Balance method enhanced by the filtering is used to evaluate the impact of unsteady turbulence on design tasks of aeroelastic interest. These are given by the prediction of the aerodynamic excitation and the aerodynamic damping, respectively. The impact of unsteady turbulence is investigated and quantified for both subsonic and transonic flow conditions. The evaluation of its quality and quantity is used to assess numerical solution approaches differing in the degree of exploited model order reduction. The assessed methods suffer from an increasing loss of information though benefit from lower requirements with regard to computational effort and run time.

ZUSAMMENFASSUNG

Die vorgelegte Promotionsschrift behandelt die Fragestellung des Einflusses instationärer Turbulenzeffekte auf die Vorhersage der aerodynamischen Anregung von Turbinen- und Verdichterkomponenten. Im Speziellen werden im Zuge der Arbeit zunächst die Ursachen für zu Beginn der Arbeit festgestellte Instabilitäten bei Anwendung des betrachteten numerischen Lösungsverfahren im Frequenzbereich identifiziert und durch Implementierung einer geeigneten Filtermethodik im Quellcode behoben.

Die Anwendung des stabilisierten Lösungsverfahrens in Verbindung mit einer entsprechenden Validierung erlaubt im Anschluss eine Bewertung des Einflusses der genannten instationären Turbulenzeffekte auf die in aeromechanischer Hinsicht relevanten Auslegungsaufgaben der Vorhersage von aerodynamischer Zwangserregung und Dämpfung. Dies wird sowohl für sub-, als auch für transsonische Strömungszustände untersucht und bewertet. Die Bewertung des Einflusses instationärer Turbulenzeffekte in Hinsicht auf Qualität und Quantität wird zur Analyse verschiedener numerischer Lösungsansätze verwendet, die aufgrund eines steigenden Grades von Modell-Ordnungs-Reduktion zunehmend unter Verlust an Information leiden, jedoch durch sinkende Anforderungen an die erforderliche Rechenleistung und Laufzeit profitieren.

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This research thesis is a result of my work at MTU Aero Engines AG in Munich, Germany. During my research work in the Aerodynamics Department, I found considerable freedom to realise my ideas as well as an environment providing valuable insight in ongoing research and design issues concerning current and future generations of aircraft engines. Without the continuous support and exchange of the entire department, this research would never have achieved the presented level of industrial relevance and impact. Therefore, I would like to express my deepest gratitude to MTU Aero Engines AG and the Aerodynamics Department in particular for giving me the opportunity to realise this research effort.

I also want to express sincere thanks to my research advisor, Prof. Dr. tekn. Damian Vogt for guiding and supervising the presented work. At crucial stages of this research, he supported this effort by pointing out the achievements and, when necessary, hinting on an insufficient state of verification.

As the academic aspect of this work was assured by my supervisor Prof. Vogt from the University of Stuttgart, the same holds for Detlef Korte from MTU Aero Engines AG for what concerns the needs faced in an industrial context. The industrial value of this work as well as its contribution to the community of aeroelasticity in general is dedicated to him as to our continuous and detailed discussions.

A large part of the credit goes to the Numerical Methods Department of the Institute of Jet Propulsion at the German Aerospace Center DLR in Cologne. At DLR Cologne, I found a team that always supported me with their interest in my work, stimulating discussions and, if necessary, the expression of concerns about the progress of my research. In particular, I want to thank Dr. Christian Frey whose impact on this work can not be emphasised enough. Without his guidance, this work would have been lost. The same holds - maybe even without his further notice - for Dr. Jan Backhaus whose comments on this work at an early stage turned out to become a real game changer.

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Even more important than the students are, obviously, the teachers. The teachers who affected me and my research the most are Dr. Anne Gerdes from intersoft AG, Germany and Dr. Lars Radtke from TU Hamburg, Germany. Their patience, tuition and the way to share their knowledge expresses itself in the way I work, think and address problems to the present day.

Finally, every seized opportunity needs a person granting the required trust in the first place. Therefore, I want to close with my final thank to Dr. Karl Engel from MTU Aero Engines AG, Germany, for a lot but the most for giving me the possibility to proof my talent in a field of research I was allowed to enter without any experience.

CONTENTS

NOMENCLATURE

ATF	Altitude Test Facility
ATRD	Advanced Turbine Research Demonstrator
BPF	Blade Passing Frequency
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
CPUh	CPU hour
DC	Direct Current, Time-Invariant Component of a Fourier Series
DLR	German Aerospace Center
DFT	Discrete Fourier Transform
EO	Engine Order
FFT	Fast Fourier Transform
HB	Harmonic Balance
HPC	High Pressure Compressor
HS	Harmonic Set
IBPA	Inter Blade Phase Angle
iDFT	Inverse Discrete Fourier Transform
iFT	Inverse Fourier Transform
LPT	Low Pressure Turbine
LE	Leading Edge
MUSCL	Monotonic Upwind Scheme for Conservation Laws
ND	Nodal Diameter

NSV	Non-Synchronous Vibration
PS	Pressure Side
Q3D	Quasi Three-Dimensional Solution Approach
RANS	Reynolds-averaged Navier Stokes Equations
SS	Suction Side
SWBLI	Shock Wave Boundary Layer Interaction
TE	Trailing Edge
TRACE	CFD Solver developed at DLR Cologne, Germany
URANS	Unsteady Reynolds-averaged Navier Stokes Equations
VPF	Vane Passing Frequency
WG	Wake Generator
WGPF	Wake Generator Passing Frequency

c	Set of Primal Navier-Stokes Quantities	[-]
CFL	Courant-Friedrich-Lewy number	[-]
d	Set of Quantities required for Turbulence Modeling	[-]
δ	Boundary Layer Thickness	[m]
δ_1	Boundary Layer Displacement Thickness	[m]
$\Delta\eta_{\mathrm{is,Stage2}}$	Deviation of Isentropic Efficiency	[%]
$\mathcal{D}$	Alternative Definition of a Differential Operator	[-]
E	Specific Total Energy of a Fluid	[$\frac{\mathrm{m}^2}{\mathrm{s}^2}$]
f	Fundamental or Base Frequency of a Flow Field	[Hz]
f_g	Specific, Local Generalised Force	[$\frac{\mathrm{N}}{\mathrm{m}^2}$]
F_g	Generalised Force	[N]
Φ	Turbomachinery Flow Coefficient	[-]
g_m	Skewness within a Measured Data Set	[-]
H_{12}	Boundary Layer Shape Factor	[-]
γ	Intermittency of a Transitional Boundary Layer	[-]
γ_δ^*	Intermittency averaged over the Boundary Layer	[-]
$\widehat{I}$	Equation System of the Discretised Flow Problem	[-]
k	Turbulence Kinetic Energy	[$\frac{\mathrm{m}^2}{\mathrm{s}^2}$]
l_U	Turbulence Length Scale	[m]
l_{ax}	Axial Chord Length	[m]
m	Harmonic Index of the HB Method	[-]

M	Truncation Order of the HB Method	[-]
Ma	Mach Number	[-]
$\mathrm{Ma}_{\mathrm{V2,in}}$	Mach Number at First Stator Exit Plane	[-]
μ	Dynamic Viscosity of a Fluid	[Pa·s]
μ_t	Eddy Viscosity of a Fluid	[Pa·s]
μ_2	Second Central Moment or Variance of Data Set	$[\mathrm{V}^2]$
μ_3	Third Central Moment	$[\mathrm{V}^3]$
N	Number of Sampling Points	[-]
p_{t}	Fluid Stagnation Pressure	[Pa]
q	Set of All considered URANS Quantities	[-]
ρ	Fluid Density	$[\frac{\mathrm{kg}}{\mathrm{m}^3}]$
ρE	Total Energy of a Fluid	[J]
ρu	Fluid Momentum	[N·s]
Π_{tot}	Overall Total Pressure Ratio	[-]
Ψ_t	Eddy Viscosity Ratio	[-]
$\widehat{R}$	Non-Linear URANS Residual in the Frequency Domain	[-]
R^*_N	Non-Linear URANS Residual at Sampling Point N	[-]
$\mathrm{Re}_{\mathrm{V2,in}}$	Reynolds number at the Second Stator Inlet Plane	[-]
Re_{Θ_t}	Transition Reynolds Number	[-]
Sr	Strouhal Number	[-]
σ	Standard Deviation of a Data Set	[V]
σ_m	Lanczos-σ Factor	[-]
t	Physical Time	[s]
T	Period of one Blade/Vane Passing	[s]
T_{t}	Total Temperature of a Fluid	[K]
T_U	Turbulence Intensity	[-]
Θ	Amplitude Modulation	[-]
τ	Pseudo Time	[-]
τ_w	Wall Shear Stress	[Pa]
θ	Boundary Layer Momentum Thickness	[m]
u	Fluid Velocity	$[\frac{\mathrm{m}}{\mathrm{s}}]$
ω	Turbulence Dissipation Rate	$[\mathrm{s}^{-1}]$
Ω	Angular Frequency	$[\mathrm{s}^{-1}]$
$\mathcal{O}_M$	Truncation Error of a Fourier Series Expansion	[-]
x	Axial Flow Direction	[m]