The Transonic Compressor with Inlet Guide Vane Asymmetry for Aerodynamic Mistuning: Effects on Aerodynamics and Aeroelasticity

Daniel Franke

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Herausgegeben von Prof. Dr.-Ing. H.-P. Schiffer

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Zur Erlangung des akademischen Grades Doktor-Ingenieur (Dr.-Ing.)
genehmigte Dissertation von Daniel Franke aus Bonn
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1. Gutachten: Prof. Dr.-Ing. H.-P. Schiffer
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In memory of my beloved mom.

Editor's Preface

This series Research Reports of the Institute of Gas Turbines and Aerospace Propulsion accounts for the advances in research and development in the field of turbomachinery at Technical Universtity of Darmstadt. Because of the strong orientation on applications in this research field, the academic problems reflect industrial development trends.

The changing political, economic and ecological framework influences the current development focus and keeps carrying the turbomachine to the border of technological feasibility. As a result, it is not unusual for findings to be directly transferred to the industrial application.

Within this environment, the industry and application oriented research works of this series originate. They describe current findings of experimental investigations and numerical simulations which were obtained at the Institute of Gas Turbines and Aerospace Propulsion at Technical University of Darmstadt.

Heinz-Peter Schiffer

Darmstadt, 2015

Author's Preface

This dissertation is part of my time as a research assistant at the Institute of Gas Turbines and Aerospace Propulsion at Technical University of Darmstadt. I had the opportunity to gain experience in various projects and teaching activities, as well as to contribute my own knowledge, backed with a lot of trust and freedom. For this I would like to thank Prof. Dr.-Ing. Heinz-Peter Schiffer.

I would like to thank Prof. Robert Kielb Ph.D. for taking over the co-supervision of my dissertation as well as the technical discussions and suggestions.

For the support in administrative and organizational topics I would like to express my sincere thanks to Ms. Löhr. Also, I would like to thank the institute's in-house workshop for the manufacturing and flexible adjustments of part as well as the support at the test rig.

The experiments for this dissertation were conducted within the framework of the Federal Aeronautical Research Programme project *LuFo-V TiGHT* (FKZ 20T1725), funded by the Federal Ministry of Economic Affairs and Climate Action as well as Rolls-Royce Deutschland Ltd & Co KG.

I would like to thank Rolls-Royce for the permission to publish the results. Thanks to the compressor aerodynamics and aeroelasticity group at Rolls-Royce Deutschland, especially Bernd Becker and Thomas Giersch, for the fruitful collaboration and technical discussions.

Reseach and working towards a Ph.D. strongly depend on a good team. I would like to express my sincere thanks to all colleagues who accompanied my time at the institute for the great adventure and fun. I am especially grateful for the support and inspiration provided by Christian, Christoph and Max, as well as the TSV2 team with Jan, Max and Silas. It is always a pleasure to work with friends.

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I would like to acknowledge the support of students, especially Alexandra, Anna, Felix, Nicolas and Thoren, for contributing to the research project and this thesis. Collaborating at the rig, developing novel data analysis methods or spending countless hours during the measurements was a rewarding experience.

My biggest thanks go to my father for his unconditional support and enabling my own path in life.

Last but not least – Vero, thanks a lot for the daily support, motivation and backup, especially in difficult times. You are an important part of all this!

Daniel Franke

Munich, 2022

Abstract

Aiming towards sustainable and safe aviation, propulsion systems play a key role. Enhanced aero engines and corresponding technology trends pronounce the susceptibility to aeroelastic instabilities, constraining innovative and disruptive designs. Understanding the mechanisms of aeroelasticity phenomena, such as non-synchronous vibration, and deriving feasible countermeasures is crucial, and remains an important focus of research activities.

The aerodynamic and aeroelastic behavior of a modern transonic compressor is investigated in this dissertation, focusing on the effects of aerodynamic mistuning based on asymmetry patterns of the variable inlet guide vanes. The experiments were carried out at the Transonic Compressor Darmstadt test rig at Technical University of Darmstadt, using extensive steady and time-resolving instrumentation, both for aerodynamic and aeroelastic analyses.

Variable inlet guide vanes have an effect on the stability behavior of a compressor, as stagger angle schedules affect the mean operating conditions of the rotor and convective characteristics of aerodynamic pre-stall disturbances. This can lead to a variety of limiting aeroelastic phenomena, depending on the rotor speed and inlet guide vane setting. The aeroelastic lock-in is only shifted with respect to the fluid-structure-interaction conditions, mainly driven by the convective characteristics of aerodynamic pre-stall disturbances. Hence, the aeroelastic challenges are still present for a wide operating range.

Asymmetry patterns of the variable inlet guide vanes alter the rotor inflow circumferentially, leading to incidence and loading variations. Performance and aerodynamics are depending on the applied pattern and corresponding flow redistribution. Rotor tip flow and related aerodynamic pre-stall disturbances are depending on the circumferential position with respect to the pattern. This leads to a circumferential rise and decay of aerodynamic disturbances depending on the throttling conditions during stall inception.

Preventing the formation of coherent propagating aerodynamic waves, based on convective aerodynamic pre-stall disturbances, and the lock-in with certain blisk modes is the fundamental mistuning mechanism. The effectiveness is evident for a wide operating range and variety of pattern designs. A minimum degree and circumferential extent of flow non-uniformity is required to provide the necessary circumferential decay and therefore, suppressed blade vibration.

Multiple design recommendations and concepts are introduced, and certain limitations are highlighted. Designing an asymmetry pattern of the variable inlet guide vanes, feasible to reduce non-synchronous vibration for part speed operating conditions with the respective schedule, minimize the forced response impact and lower performance degradation at design speed, is possible.

The findings of this work contribute to a better understanding of convective non-synchronous vibration in transonic compressors, highlight influencing parameters regarding the variable inlet guide vanes and demonstrate a promising approach of aerodynamic mistuning with intended stagger angle asymmetries in vane rows.

Kurzfassung

Auf dem Weg zu einer nachhaltigen und sicheren Luftfahrt spielen die Antriebsysteme eine Schlüsselrolle. Verbesserte Flugzeugtriebwerke und entsprechende Technologietrends steigern die Anfälligkeit hinsichtlich aeroelastischer Instabilitäten, und erschweren innovative und disruptive Entwicklungen. Das Verständnis der Mechanismen aeroelastischer Phänomene, wie zum Beispiel nicht-synchrone Schwingungen, und die Ableitung praktikabler Gegenmaßnahmen ist von entscheidender Bedeutung und bleibt ein wichtiger Schwerpunkt in Forschungsaktivitäten.

In dieser Dissertation wird das aerodynamische und aeroelastische Verhalten eines modernen transsonischen Verdichters untersucht. Dabei liegt der Schwerpunkt auf den Auswirkungen des aerodynamischen Mistunings mittels asymmetrischer Muster der variablen Eintrittsleitradschaufeln. Die Experimente wurden am Transsonischen Verdichterprüfstand der Technischen Universität Darmstadt durchgeführt. Dabei wird umfangreiche stationäre und zeitauflösende Messtechnik eingesetzt, um aerodynamische und aeroelastische Analysen zu ermöglichen.

Variable Eintrittsleiträder beeinflussen das Stabilitätsverhalten eines Verdichters, da sich die Staffelungswinkel der Schaufeln auf die Betriebsbedingungen des Rotors und somit auf die konvektiven Eigenschaften aerodynamischer Störungen an der Stabilitätsgrenze auswirken. Dies kann zu einer Vielzahl von aeroelastischen Phänomenen führen, die den stabilen Betrieb begrenzen, und von der Rotordrehzahl sowie der Verstellung der Eintrittsleitradschaufeln abhängen. Fluid-Struktur-Interaktionen und der aeroelastische Lock-in werden in Abhängigkeit der konvektiven Eigenschaften der aerodynamischen Störungen an der Stabilitätsgrenze lediglich verschoben. Folglich treten die aeroelastischen Herausforderungen weiterhin über einen breiten Betriebsbereich auf.

Asymmetrische Muster der variablen Eintrittsleitradschaufeln verändern die Rotoranströmung über den Umfang, was zu Variationen der Inzidenzen und aerodynamischen Belastung führt. Die Leistungsfähigkeit und Aerodynamik hängen von dem verwendeten Muster und der entsprechenden Umverteilung der Strömung ab. Die Strömungsbedingungen an der Rotorschaufelspitze und die damit verbundenen aerodynamischen Störungen in der Nähe der Stabilitätsgrenze sind abhängig von der Umfangsposition relativ zum Muster. Dies führt zu einem Ansteigen und Abklingen der aerodynamischen Störungen über den Umfang, abhängig von den Drosselbedingungen vor dem Erreichen der Stabilitätsgrenze.

Der grundlegende Mistuning-Mechanismus beruht auf der verhinderten Bildung von sich kohärent ausbreitenden aerodynamischen Wellen, basierend auf konvektiven aerodynamischen Störungen, und dem entsprechenden Lock-in mit bestimmten Blisk-Moden. Die Wirksamkeit kann für einen weiten Betriebsbereich und eine Vielzahl von Musterausführungen gezeigt werden. Dabei ist ein Mindestmaß der Strömungsunförmigkeit in Umfangsrichtung erforderlich, um die notwendige Abschwächung zu erreichen, und somit Schwingungen zu unterbinden.

Es werden einige Konstruktionsempfehlungen und Konzepte vorgestellt sowie bestimmte Einschränkungen hervorgehoben. Es ist möglich, ein asymmetrisches Muster der variablen Eintrittsleitradschaufeln zu entwerfen, das die nicht-synchronen Schwingungen bei Teillastbetrieb mit entsprechender Schaufelverstellung reduziert, die Auswirkungen auf erzwungene Schwingungen minimiert und Leistungseinbußen bei Auslegungsdrehzahl verringert.

Die Erkenntnisse dieser Arbeit tragen zu einem besseren Verständnis der konvektiven nicht-synchronen Schwingungen in transsonischen Verdichtern bei, zeigen Einflussparameter bezüglich der variablen Eintrittsleitradschaufeln auf und demonstrieren einen vielversprechenden Ansatz des aerodynamischen Mistunings mittels beabsichtigten Anstellwinkelasymmetrien in Schaufelreihen.

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Nomenclature

Latin Symbols

a	m/s	Speed of sound
A	m^2	Area
c	m/s	Absolute velocity
c_p	J/kg K	Specific heat capacity at constant pressure
f	Hz	Frequency
h	J/kg	Specific enthalpy
$\dot{m}$	kg/s	Mass flow
Ma	-	Mach number
n_{aero}	-	Aerodynamic cell count
N_{blade}	-	Blade count
p	Pa	Pressure
P	W	Power
R	J/kg K	Specific gas constant
s	J/kg K	Specific entropy
T	K	Temperature
u	m/s	Tangential velocity
v	m/s	Propagation velocity
w	m/s	Relative velocity

Greek Symbols

α	°	Tangential flow angle
β	°	Stagger angle, incidence angle
Δ	-	Difference
η	-	Efficiency
κ	-	Heat capacity ratio
π	-	Pi (Archimedes' constant)
Π	-	Pressure ratio

ρ	kg/m^3	Density
σ	-	Standard deviation
τ	-	Temperature ratio
φ	rad	Interblade phase angle
ω	1/s	Rotational frequency

Subscripts and Superscripts

$\square^{A}$	Environmental conditions A
$\square^{B}$	Environmental conditions B
$\square_{20,21,30}$	Measurement sections
$\square_{aa}$	Area averaged
$\square_{aero}$	Aerodynamic
$\square_{ax}$	Axial
$\square_{blade}$	Rotor blade
$\square_{C}$	Compressor
$\square_{cell}$	Rotating stall cell
$\square_{circ,u}$	Circumferential
$\square_{corr}$	Corrected
$\square_{DMW}$	Torque measurement system
$\square_{dyn}$	Dynamic
$\square_{ensemble}$	Ensemble-averaged
$\square_{exc}$	Excitation
$\square_{inlet,in}$	Inlet
$\square_{is}$	Isentropic
$\square_{max}$	Maximum
$\square_{mean}$	Mean value of parameter
$\square_{nom,PE}$	Normalized with nominal N100 PE
$\square_{outlet,out}$	Outlet
$\square_{PP}$	Pitch passing
$\square_{r}$	Rotational
$\square_{red}$	Reduced
$\square_{rel}$	Relative
$\square_{rot}$	Rotating frame of reference
$\square_{s}$	Static
$\square_{stat}$	Stationary frame of reference
$\square_{std}$	Standard deviation
$\square_{t}$	Total
$\square_{tip}$	Tip section

Abbreviations

1F	First flap blade mode
1T	First torsional blade mode
3D	Three dimensional
5HP	Five hole probe
ACARE	Advisory Council for Aeronautic Research in Europe
am	Aerodynamic mistuning
ax	Axial
blisk	Blade-integrated-disk
BTT	Blade tip timing
CFD	Computational Fluid Dynamics
circ	circumferential
CO_2	Carbon dioxide
EO	Engine order
FSI	Fluid-structure-interaction
HCF	High cycle fatigue
IGV(A)	Inlet guide vane (angle)
ISA	International Standard Atmosphere
LE	Leading edge
M4	Blade mode 4
MS	Measurement section
N(100)	Rotor speed in percentage design speed
NC	Near choke
ND	Nodal diameter
nom	nominal
NO_x	Nitrogen oxides
NS	Near stall
NSV	Non-synchronous vibration
PE	Peak efficiency
PIV	Particle image velocimetry
PS	Pressure side
RI	Rotor inlet
RO	Rotor outlet
SE	Stage exit
SG	Strain gauge
SI	Stage inlet
SM	Stability margin
SS	Suction side
TA / TB	Transition A / B

TCD	Transonic Compressor Darmstadt
TE	Trailing edge
TUDa	Technical University of Darmstadt
VI	VIGV inlet
VIGV	Variable inlet guide vanes
VSV	Variable stator vanes
WPT	Wall pressure transducer