Coupling of tip leakage flow and blade vibration in transonic compressors

Mechanism and countermeasures

Felix Holzinger

TECHNISCHE UNIVERSITÄT DARMSTADT

Band 9 / 2018

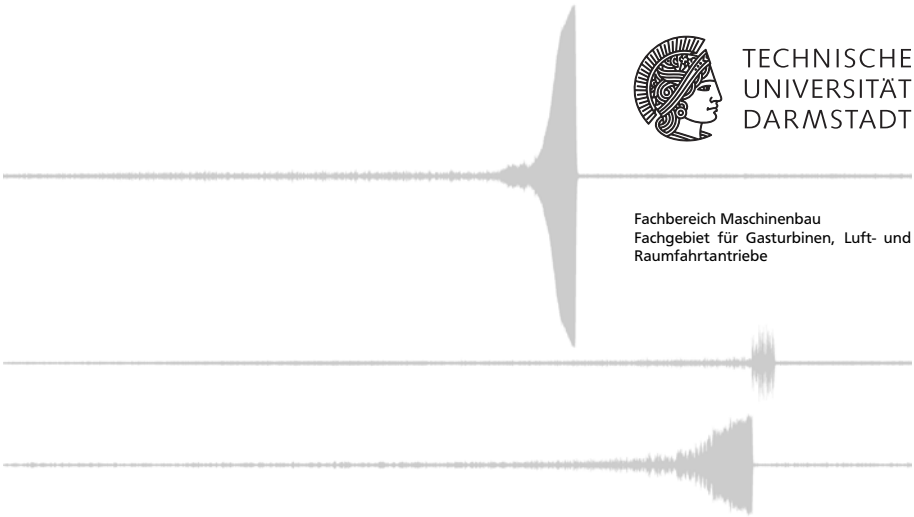
Forschungsberichte aus dem Institut für Gasturbinen, Luft- und Raumfahrtantriebe

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

Coupling of tip leakage flow and blade vibration in transonic compressors - Mechanism and countermeasures

Kopplung von Spitzenspaltströmung und Schaufelschwingung in transsonischen Verdichtern - Mechanismus und Gegenmaßnahmen
Zur Erlangung des akademischen Grades Doktor-Ingenieur (Dr.-Ing.)
genehmigte Dissertation von Felix Holzinger aus Bayreuth
Tag der Einreichung: 27. Juni 2017, Tag der Prüfung: 24. Oktober 2017
Darmstadt — D 17

1. Gutachten: Prof. Dr.-Ing. H.-P. Schiffer
2. Gutachten: Prof. Dr.-Ing. habil. R. Mailach



TECHNISCHE UNIVERSITÄT DARMSTADT

Fachbereich Maschinenbau
Fachgebiet für Gasturbinen, Luft- und Raumfahrtantriebe

Coupling of tip leakage flow and blade vibration in transonic compressors - Mechanism and countermeasures
Kopplung von Spitzenspaltströmung und Schaufelschwingung in transsonischen Verdichtern - Mechanismus und Gegenmaßnahmen

Genehmigte Dissertation von Felix Holzinger aus Bayreuth

1. Gutachten: Prof. Dr.-Ing. H.-P. Schiffer
2. Gutachten: Prof. Dr.-Ing. habil. R. Mailach

Tag der Einreichung: 27. Juni 2017
Tag der Prüfung: 24. Oktober 2017

Darmstadt — D 17

Forschungsberichte aus dem Institut für Gasturbinen,
Luft- und Raumfahrtantriebe

Band 9

Felix Holzinger

Coupling of tip leakage flow and blade vibration in transonic compressors

Mechanism and countermeasures

D 17 (Diss. TU Darmstadt)

Shaker Verlag
Aachen 2018

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Darmstadt, Techn. Univ., Diss., 2017

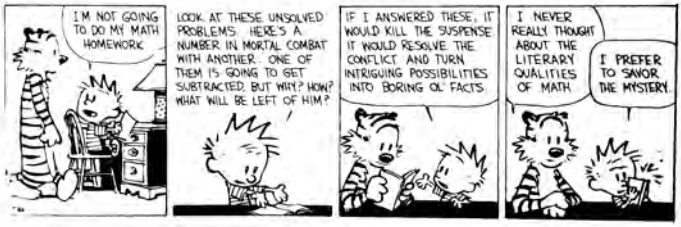
Printed in Germany.

ISBN 978-3-8440-5823-9
ISSN 2364-4761

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

Flutter prediction is very complex.
- Rolls-Royce

Dank Elli.
Dank einem sehr guten Fachgebiet.
And thanks to all FUTURE partners and Rolls-Royce.



Und
weil wir es können.

Editor's preface

The series *Research Reports from the Institute of Gas Turbines and Aerospace Propulsion* accounts for the advances made in turbomachinery research and development at Technische Universität Darmstadt. Because of the strong application oriented focus of the research in this area, the academic problems reflect actual industrial development trends.

The current development foci adapt to the changing political, economic and ecological framework which keeps carrying the turbomachine towards the border of technological feasibility. In consequence, it is not unusual for findings to be transferred to the industrial application directly.

It is within this environment, that the industry and application oriented research works of this series originate. The reports describe current findings of experimental investigations and numerical simulations which were obtained at the Institute of Gas Turbines and Aerospace Propulsion at Technische Universität Darmstadt.

Heinz-Peter Schiffer

Darmstadt, 2017

Abstract

This dissertation describes the aeroelastic results obtained with a state-of-the-art research compressor representative to the high pressure compressor front stage of a modern twin-shaft turbofan engine.
The 1.5-stage compressor with blisk rotor was designed jointly by Rolls-Royce and TU Darmstadt as technology demonstrator for secondary flow control. In the present context, the 1.5-stage compressor is investigated with different tip clearance sizes as well as advanced casing treatment. In order to resolve the fluid-structure interaction behind the encountered blade vibrations, the compressor is heavily instrumented with unsteady wall-pressure transducers, blade mounted strain gauges and capacitive blade tip clearance/blade tip timing sensors.
This dissertation focuses on the aeroelastic behavior of the blisk rotor in the high back-pressure region. In particular, flutter and a self-excited rotating instability are investigated. It is shown for both phenomena that the aeroelastic link establishes at blade tip between periodic blade motion and fluctuating tip flow. In both cases, a backward traveling aerodynamic wave couples with a forward traveling blade vibration. The crucial role of the blade tip clearance and the flow leaking across blade tip is clearly exhibited. Both gain additional relevance from the observation that a 10% variation in local tip clearance may cause individual blade vibration amplitudes to vary by a factor of two.
Flutter and self-excited rotating instability occur at design speed with transonic rotor relative inflow as well as in the subsonic part speed region. Circumferential wave speed and wave Mach number of the backward waves are identified as common link between the blade vibration events at different compressor speeds with seemingly arbitrary active nodal diameter. It is further shown that the vibration wave Mach number correlates with the circumferential Mach number of a rotating stall cell at identical speed with nominal variable inlet guide vane setting.
Finally, the dissertation proves that the aeroelastic coupling can be broken up and high amplitude blade vibration can be prevented by either a reduction in average tip clearance or by aerodynamic mistuning through advanced casing treatment. The negation of this final conclusion implies that an increase in tip clearance due to transient operation, rub-in or component wear may lead to the onset of blade vibrations not encountered with nominal clearance. The dissertation thus clearly points out that blade vibration analyses have to be robust enough to cover the compressor's entire life cycle.

Table of contents

Nomenclature **IX**

List of figures **XV**

List of tables **XIX**

1 Introduction **1**

2 Problem statement **7**

3 Fundamentals **11**
3.1 Foreword to the *Fundamentals* section 11
3.2 Gas turbine layout and cycle 12
3.2.1 The gas generator - heart of any gas turbine 12
3.2.2 Motivation for global design trends 16
3.3 Axial compressors 18
3.3.1 Axial layout 18
3.3.2 Multistage layout 19
3.3.3 Euler equation 20
3.3.4 Transonic layout 23
3.3.5 Secondary flow in axial compressors 26
3.3.6 3D-design of axial compressor rotors 29
3.3.7 Compressor performance and operation 31
3.4 Blade tip clearance 36
3.4.1 Transient variation of the global tip clearance 37
3.4.2 Tip clearance variations of the individual blades 39
3.5 Blade vibration 42
3.5.1 Inferior damping of rotors 42
3.5.2 Relation of mean and alternating stresses 43
3.5.3 Blade eigenmodes 45
3.5.4 Campbell diagram 48
3.5.5 Nodal diameters and traveling waves 51
3.5.6 Mistuning 55

4 Flow induced blade vibration **57**
4.1 Need for a new categorization of flow induced blade vibration . 57
4.2 Novel categorization of flow induced blade vibration 59
4.2.1 Synchronous vibration 60
4.2.2 Non-synchronous vibration 61

5 Test rig, test compressor and transient experiments **67**
5.1 TU Darmstadt Transonic Compressor Test Rig 67
5.1.1 Research background 68
5.1.2 Research facility 69
5.2 Transonic research compressor V1R5S3 69
5.3 Aerodynamic performance instrumentation 71
5.4 Instrumentation for aeroelastic experiments 72
5.4.1 Rotor strain gauges (SG) 72
5.4.2 Blade tip clearance / blade tip timing (BTC/BTT) 74
5.4.3 Fast response wall pressure transducers (WPT) 75
5.5 Investigated configurations 76
5.5.1 Reference clearance 77
5.5.2 Large clearance 77
5.5.3 Non-axisymmetric casing treatment 77
5.5.4 Blade tip clearance comparison 77
5.6 Rotor 5 blisk with one locally damaged rotor blade tip 79
5.7 Transient experiments 80
5.7.1 Experimental procedure 80
5.7.2 Determination of the transient aerodynamic performance 82
5.7.3 Determination of active blade mode and nodal diameter 82

6 Experimental results **84**
6.1 Overview of the stability limits 84
6.2 Identification of the limiting phenomena 86
6.2.1 M2 flutter 86
6.2.2 Rotating stall 89
6.2.3 Rotating instabilities 90
6.2.4 M1 flutter 93
6.2.5 NASCT resonance followed by rotating stall 96
6.3 Aeroelastic sensitivity to transient blade tip clearance variations 100
6.4 Coupling mechanism 104
6.4.1 Role of the tip leakage flow 104
6.4.2 Tip flow fluctuation and unsteady blade force 108
6.4.3 Evolution of the traveling waves 113

6.4.4 Coupling of aerodynamic and structural traveling waves 118
6.4.5 Summary of the coupling mechanism 121
6.5 Countermeasures 123
6.5.1 Reduction of tip flow unsteadiness 124
6.5.2 Aerodynamic mistuning through NASCT 127
6.5.3 Limitations of countermeasures 129
6.6 Aeroelastic impact of real geometry effects 130
6.6.1 Inhomogeneous rotor blade tip clearance 130
6.6.2 Local blade damage 135
6.6.3 Impact on individual blade vibration amplitudes 137
6.7 Global assessment of the experimental results 142
6.7.1 Critical speeds related to non-synchronous vibration . . . 142
6.7.2 Wave speed 143
6.7.3 Wave Mach number 147
6.7.4 Evaluation 150

7 Conclusion **152**
7.1 Summary 152
7.2 Outlook 158
7.2.1 Deepening the insight 158
7.2.2 Extending the scope 159
7.3 Acknowledgement 161

8 Appendix **A1**
8.1 Globally averaged concentration of greenhouse gases A1
8.2 Turbojet and turbofan thrust A2
8.3 Turbojet and turbofan h-s-diagrams A3
8.4 Relation of adiabatic and polytropic compressor efficiencies . . . A6
8.5 Historical aspects concerning the stage pressure ratio A6
8.6 Amendment to blade tip clearance A8
8.7 Amendment to flow induced vibration A11
8.8 Amendment to critical NSV-related speeds A15
8.9 Amendment to aeroelastic instrumentation A17
8.9.1 Unsteady casing instrumentation A17
8.9.2 Radial pressure transducer array A22
8.10 Amendment to aerodynamic performance instrumentation . . . A23
8.11 Amendment to FUTURE compressor A25
8.12 Amendment to experimental results A26
8.12.1 Large clearance (LC) A28
8.12.2 Reference clearance (RC) A39

8.12.3 Non-axisymmetric casing treatment (NASCT) A50