Technische Universität Berlin

CHAIR OF AERO ENGINES

CHAIR OF AERO ENGINES

HEAD OF CHAIR

PROF. DR.-ING.

DIETER PEITSCH

The rapidly increasing demand of mobility in the last decades urgently requires the improvement of technology in this area to address the environmental and economic needs in the light of limited natural resources. This is especially relevant in air traffic, since a significant and continuous growth is seen in this area. Furthermore, the impact of air travel onto the atmosphere is significant and needs to be minimized.

Aeronautics is looking back on a long tradition in Berlin. Already in 1871 an association for airships was founded and only twenty years later the famous flight pioneer Otto Lilienthal climbed on a mountain only a few kilometers away from today's Charlottenburg campus to test his first glider. The continuous interest in aviation led to the foundation of the "Academic Flightgroup Berlin" in 1920 at the Technische Hochschule Charlottenburg. In 1923 the first airplanes took off at the Tempelhof airport offering a test facility for the university.

Ever since, the design of airplanes and its components is playing an important role in research and education in Berlin. Today, the department of Aeronautics and Astronautics (ILR) at TU Berlin aims to cover today's needs in a system-oriented approach.

Consequently, the structure of the department reflects the airborne traffic system in a well-to-wheel approach. A key

aspect of this approach is the propulsion and so, the chair of aero engines has been a nucleus for the development of ILR straight from its establishment.

Today, the activities of the chair focus on air breathing engines and turbomachinery. Prof. Dr.-Ing. Dieter Peitsch was appointed as head of the department in 2006, succeeding Prof. Dr.-Ing. Jean Hourmouziadis, who retired in 2005. Prof. Peitsch started his engineering career in 1985 at RWTH Aachen, achieving his diploma in jet engines and turbomachinery in 1990. Furthering his scientific career, he worked as a research assistant in the department of jet propulsion and turbomachinery at RWTH Aachen. His dissertation dealt with the aeroelastic coupling of oscillating turbomachinery blades with aerodynamics and led to the doctor degree summa cum laude in 1996.

To extend his competence for the whole engine, Prof. Peitsch joined BMW Rolls-Royce (today Rolls-Royce Deutschland), starting with a secondment to the RR performance department in Derby, U.K.. During his 10 year engagement he has led the departments of transient performance, whole engine systems and controls & transmissions engineering. During this time, he was also responsible for the development of technology in specific areas as well as for the definition of complex systems such as the TP400-D6 engine's secondary air, oil and heat management system. Backed up with this experience, Prof. Peitsch today emphasizes the holistic view on the system "Gas Turbine" including all its subsystems within research and teaching.

Consequently, three strategic areas of activities have been defined

- steady and unsteady flows in compressors and turbines
- whole engine aspects of gas turbines including secondary systems, operation and controls
- interaction of turbomachinery aerodynamics with acoustics and structure

These three areas are looked into in-depth within projects addressing specific goals, but always treated as connected to each other to gain an understanding of the interaction and the dependence between all of them. This approach is also reflected by the constitution of a strategic cooperation with the German Aerospace Center (DLR). Engine Acoustics, engine performance and turbomachinery aeroelasticity are the topics, included herein jointly with different departments of DLR.

This brochure gives an overview of the current projects at the chair of aero engines and serves as a snap shot of the status of today. As science develops, it will certainly need a continuous update.

ORGANIGRAM

Technische Universität Berlin
Faculty V
Institute of Aeronautics and Astronautics

Chair of Aerodynamics

Chair of Flight Operation & Air Traffic Management

Chair of Flight Mechanics, Flight Control & Aeroelasticity

Chair of Aero Engines

Chair of Aircraft Design & Aero Structures

Chair of Astronautics

Office
Astrid Stollfuß

Head of Chair
Prof. Dr.-Ing. Dieter Peitsch

Design Engineer
Dipl.-Ing. Horst Mudrack

Workshop
12 - man strong team

Electrical Technician
Norbert Scholz

Aeroelasticity
Research Assistants
M.Sc. Leonie Malzacher

Compressor Aerodynamics
Research Assistants
Dipl.-Ing. Christian Beselt
Dipl.-Ing. Alexander Heinrich
Dipl.-Ing. Christine Tiedemann

Hot Acoustic Test Rig
Research Assistants
Dipl.-Ing. Tobias Schliwka

JetsDreams / CO_2NCEPT
Supervisors
Dipl.-Ing. Martin Bolemant
Dipl.-Ing. Alexander Heinrich

Whole Engine Simulation
Research Assistants
Dipl.-Ing. Martin Bolemant
Dipl.-Ing. Dominik Woelki

Turbine Aerodynamics
Research Assistants
Dipl.-Ing. Christian Brück
Dipl.-Ing. Katja Hummel
Dipl.-Ing. Christoph Lyko

LECTURES

- Aero Engines I / II
- Thermal Turbomachinery I / II
- Gas & Steam Turbines (Design & Operation)
- Performance & Systems of Aero Engines
- Design of Turbomachinery
- Space Propulsion Systems
- Environmental Impacts of Aero Engines
- Aeroelasticity of Turbomachinery Blades

$$\rho_h = \frac{\Delta h_{rotor}}{\Delta h_{stage}}$$

Our goal is to impart a profound understanding of the concept of airbreathing engines and turbomachinery. The basic lectures are Thermal Turbomachinery I and Aero Engines I dealing with the fundamentals of gas turbines for all kind of propulsion as well as the thermodynamic cyclic processes and the engine components as propeller, intake, compressor, combustion chamber, turbine and nozzle. Other aspects treated are the safety and reliability requirements as well as certification of engines.

$$\frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{\frac{\kappa-1}{\kappa}}$$

$$F_S = c_9 - c_0$$

The **advanced lectures** (Thermal Turbomachinery II, Aero Engines II) are dealing with the operating behavior of the machine, the performance requirements including a customer point of view and the systems which are relevant for the machine, especially the secondary air system, the oil- and heat management and the control system. Furthermore those lectures cover the design and different configurations of thermal turbomachinery, machine operating characteristics and blade designs.

$$\psi = \frac{\Delta h_0}{u^2}$$

$$\phi = \frac{c_m}{u}$$

$$\Delta h = \frac{c_2^2 - c_1^2}{2} + \frac{u_2^2 - u_1^2}{2} - \frac{w_2^2 - w_1^2}{2}$$

The lecture Design of Turbomachinery draws the attention to the structural mechanics of rotating components, the mounting and the material selection for high temperature application. The performance of aero engines imparts the interactions of the different systems within an aero engine. As a reflection of the increasing environmental impact of aero engines the chair offers a lecture dealing with the environmental impact of aero engines.

$$\Delta h_{01-02} = c_p(T_{01} - T_{02}) = c_p T_{01}\left[1 - \left(\frac{p_{02}}{p_{01}}\right)^{\frac{\kappa-1}{\kappa}}\right]$$

A **practice oriented education** is continuosly ensured by invited guest speakers from industry as well as student projects.

$$\psi_h = \frac{\Delta h}{\frac{u^2}{2}} = \frac{2\Delta h}{\pi^2 D^2 n^2}$$

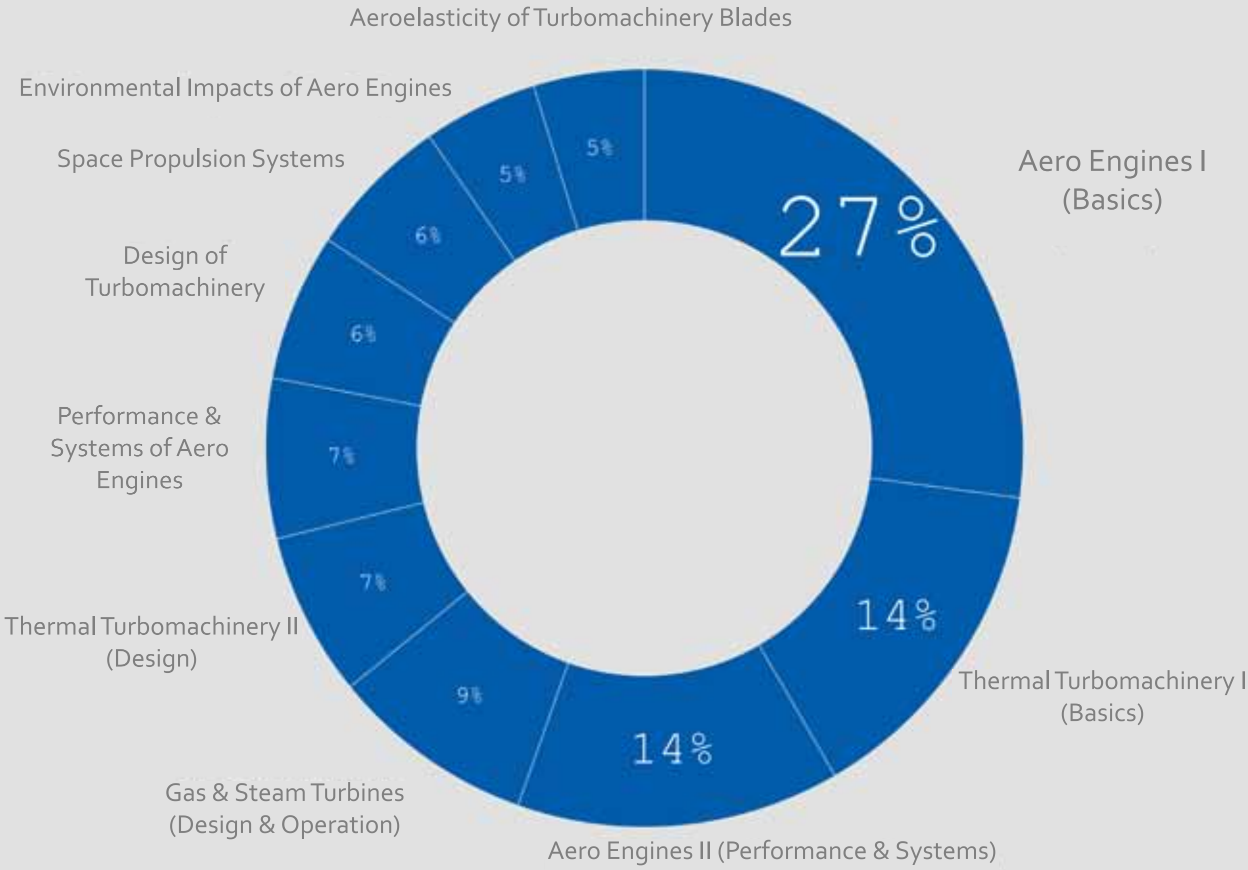
$$\eta_P = \frac{2}{1 + \frac{c_9}{c_0}}$$

$$\Delta h = u_2 \cdot c_{u2} - u_1 \cdot c_{u1}$$

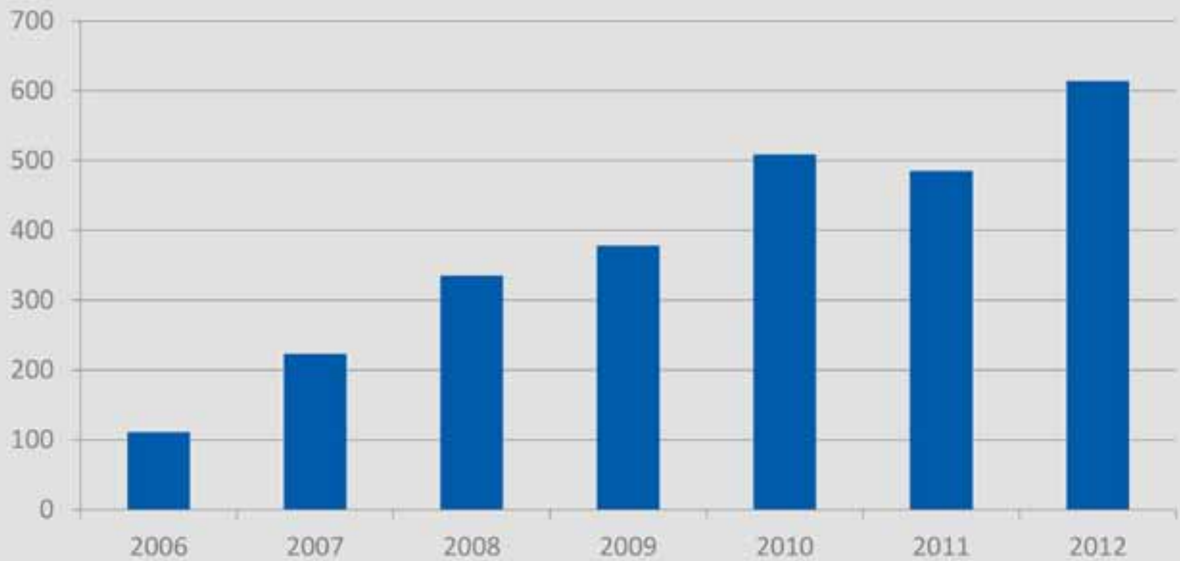
$$h_{rot} = h_{t,rel} - \frac{u^2}{2}$$

$$\mu = \frac{\dot m_{II}}{\dot m_I}$$

Statistical Distribution of Students over all Lectures (2012)



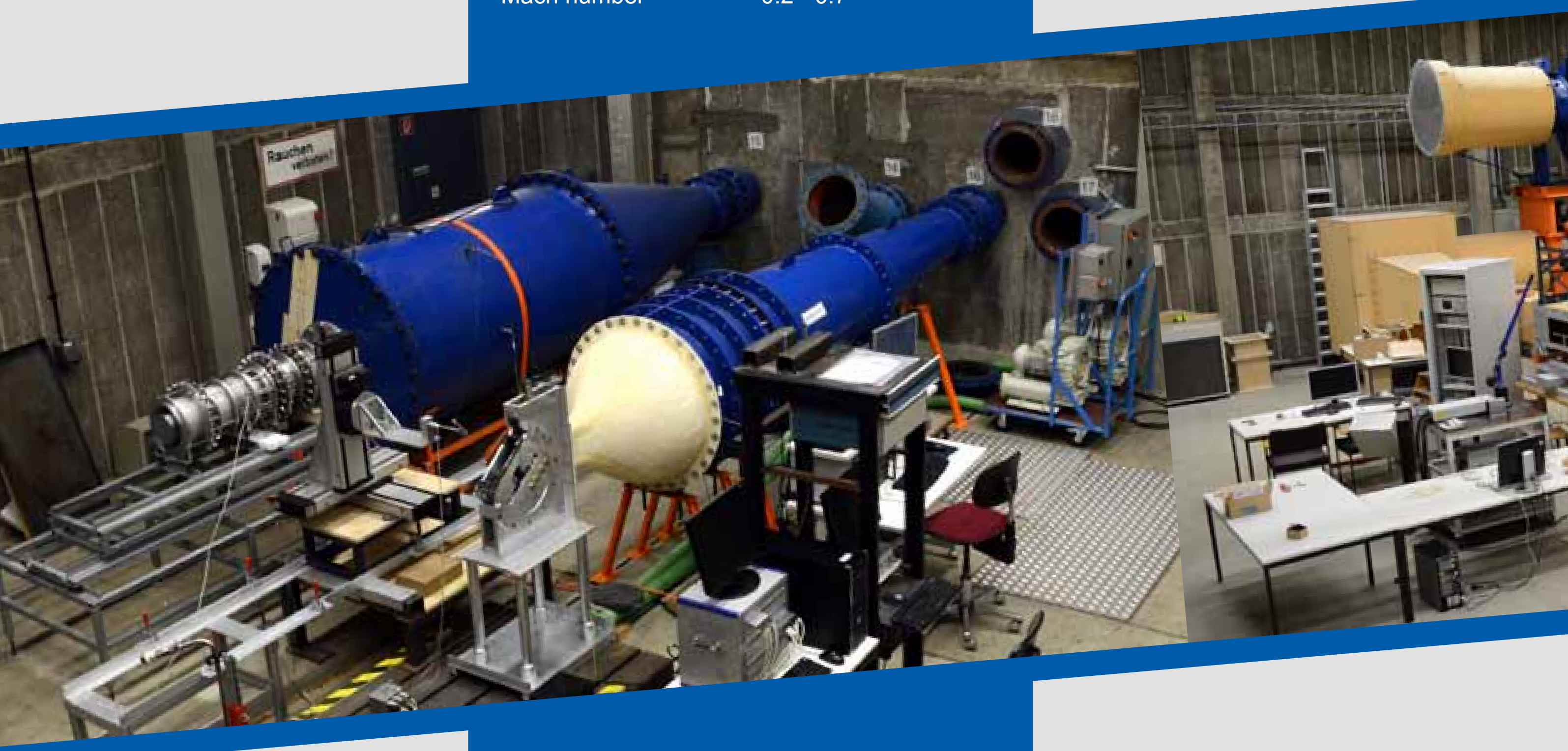
Annual Number of Students



Test Facilities

Annular High Speed Compressor Stator Cascade

Length	2.0 m
Outer diameter	0.24 m
Inner diameter	0.172 m
Incidence angle	0 - 21 deg
Max. mass flow rate	4.5 kg/s
Mach number	0.2 - 0.7



Linear High Speed Compressor Stator Cascade

Mach number	0.3 - 0.8
Max. total mass flow rate	4.5 kg/s
Turbulence level	< 1 %
Number of blades	7 + 2
Incidence angle	± 10 deg

Single and tandem blade configurations

Secondary air supply for AFC experiments

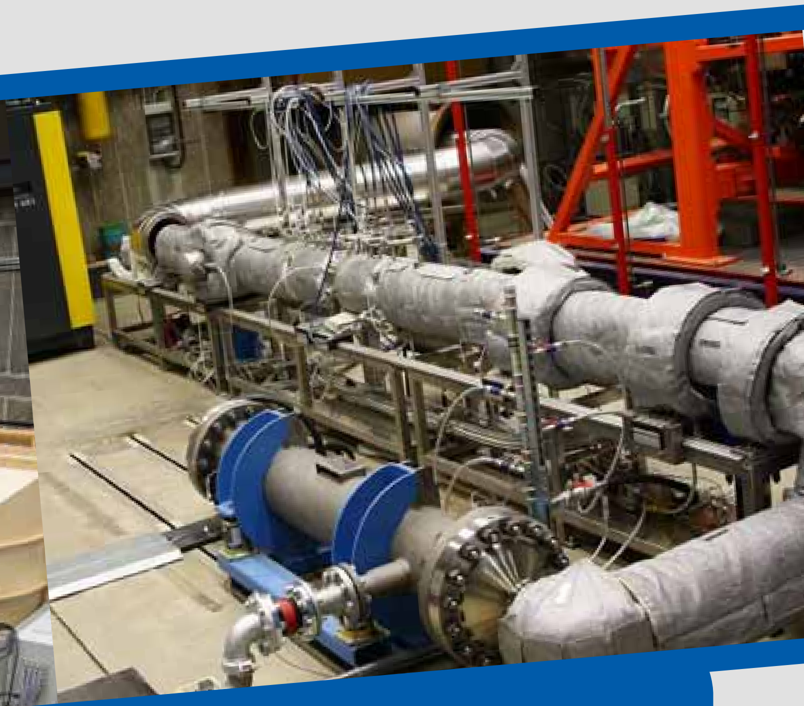
Double Stream Wind Tunnel

Cross section	2 x 0.3m x 1.0m
Mean flow speed	up to 60 m/s
Turbulence level	0.3%

Both flows separately adjustable

Shear layer flow mixing investigantions

Highest flexibility through modular design



Unsteady Low Speed Wind Tunnel

Square cross section	0.4 m x 0.4 m
Length	1.5 m
Turbulence level	0.3-15%
Mean flow speed	0-50 m/s
Velocity fluctuations	0-25 Hz
Relative amplitude	0-75% of the mean flow
Nozzle contraction ratio	9 : 1

Traverses for pressure and hot wire probes

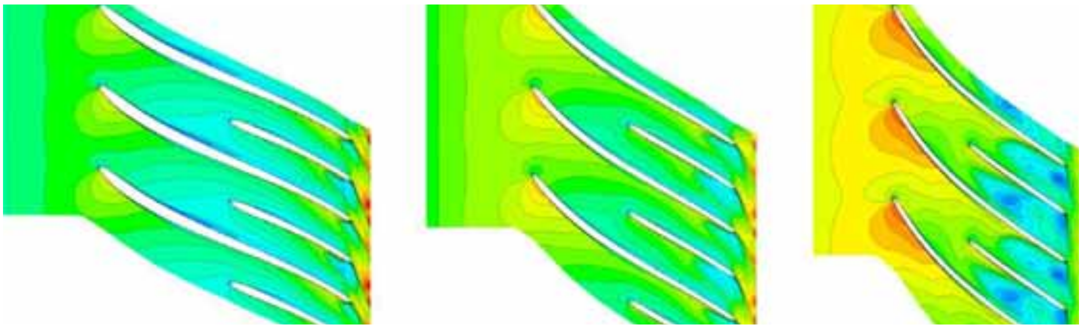
Large visualization window for stereoscopic PIV

Modular wall shape to produce 2D pressure distri-butions

Hot Acoustic Test Rig (HAT)

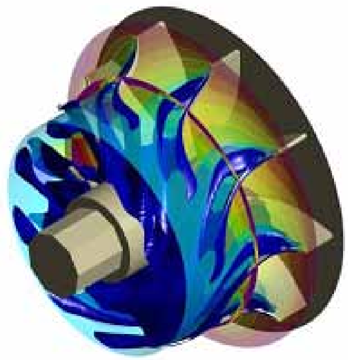
Rectangular cross section	45 mm x 90 mm
Duct Diameter	70 mm
Max. pressure	10 bar
Max. total mass flow rate	0.78 kg/s
Mach number	up to 0.7
Frequency range	160 - 2800 Hz
Max. mean flow temperature	800 K

Secondary cold flow to investigate flow interactions



Computational Fluid Dynamics

Computational fluid dynamics are employed to solve and analyze 2D and 3D fluid flow problems with different numerical methods. At the ILR CFD Simulations are performed in the range of

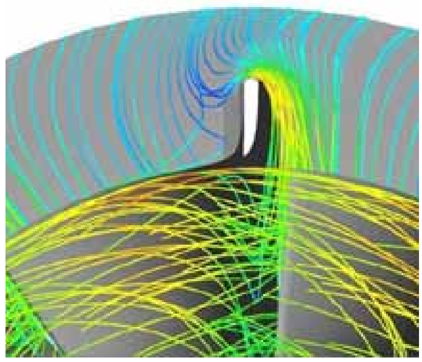


- wind tunnel design
- radial turbomachinery
- axial turbomachinery
- tandem blades
- mixing flows in high pressure turbines

A long term objective is to develop methods for blade design taking aeroelastic phenomena into account.

Hardware structure

- 6 x 64-Bit Intel Xeon 2,66 Ghz Quad Core CPUs
- 20 x 64-Bit Intel Xeon 5600Serie Westmere 2,4 Ghz Quad Core CPUs
- 288 GB RAM
- 13,5 TB HDD capacity
- 1 Network Attached Storage (NAS) mit 8 x 2000 GB HITACHI HDD (3 Gb/s SATA, 7200 U/min)
- SUSE Linux Enterprise Server 10 operationsystem, SSH Network protocol



Available Software

CFD: Ansys CFX, Fluent, Turbogrid, Trace, Flowmaster
CAD: Unigraphics NX, CalculiX, SolidWorks
CAE: Matlab/Simulink

Whole Engine Simulation

Computer models for gas turbine performance synthesis simulation are employed in order to

• conduct cycle studies for new engine concepts (Design calculation) and

• predict engine behaviour throughout the flight envelope (Off-Design calculation).

Therefore the ILR is currently using two performance simulation tools, namely the commercial software GasTurb and DLR's recent performance synthesis code GTlab.

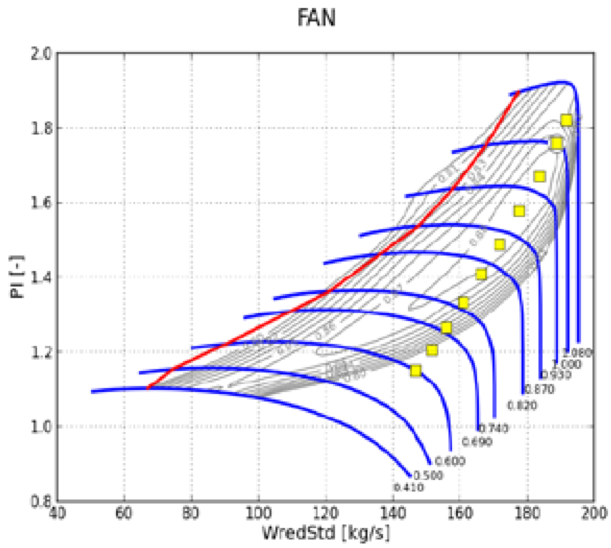
The motivation for using GTlab is to provide a performance tool capable of the following tasks and requirements:

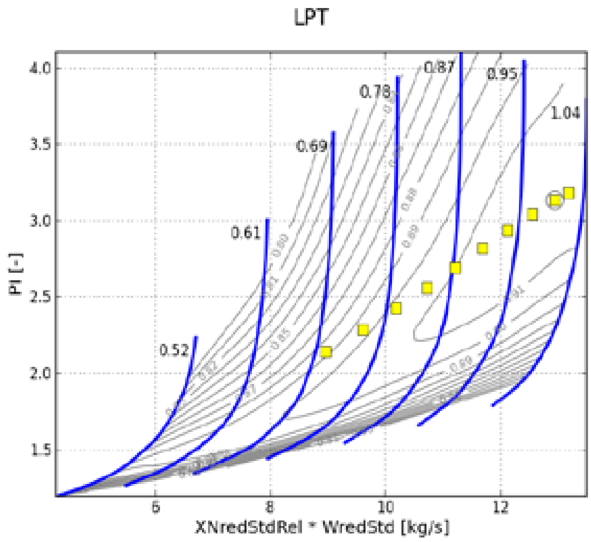
- arbitrary concepts of thermodynamic cycles
- both stationary gas turbines and propulsion
- simulation of steady state and transient behaviour
- simple integration into external simulation environments
- simple portability to partners'/customers' system environment
- high flexibility, maintainability and sustainability by taking advantage of object-oriented programming

Based on a cooperation agreement between DLR and ILR , the chair of aero engines is directly involved in the development of the GTlab code. GTlab is applied to research projects such as optimization of secondary air system flows for different operating conditions.

Future activities within this area of research will focus on

- transient simulation,
- engine control,
- evaluation of component deterioration,
- evaluation of new gas turbine engine concepts (e.g. IRA-concept),
- fully integrated component zooming.





Whole Engine Simulation

The whole engine simulation is currently performed within two projects. One is dealing with the developement of an intelligent variable stator vanes control algorithm for improved compressor operation. The second project's goal is the optimization of secondary air system flows in different operating conditions.

Development of an Intelligent Variable Stator Vanes Control Algorithm

The requirements for high pressure compressors of modern aero engines in terms of delivered pressure ratio are rising due to the request for more and more efficient engines. In order to maintain acceptable part load performance modern multistage compressors are usually equipped with variable geometries as handling bleed valves (HBV) or variable stator vanes (VSV).

Within current applications variable stator vanes of high pressure compressors are interconnected by a ganged VSV system. The control schedule is optimized regarding efficiency and surge margin on the basis of the steady state working line. The schedule is set up as a function of aerodynamic high pressure shaft speed. When leaving the steady state working line due to

- variations in environmental conditions,
- engine deterioration or
- transient maneuver,

the VSV schedule becomes inefficient. The control algorithm of variable stator vanes holds high potential regarding cycle optimization and operating range extension for a fixed engine design.

Objective

The projects aim is to develop an intelligent adaptive VSV-Control algorithm which is capable of reacting to deviations from normal operation (in terms of environmental as well as engine condition). Thereby the focus will be on optimizing the system regarding block fuel burn and extension of the operating range in steady state as well as transient operation.

Besides the development of a new generic control algorithm it is investigated whether an uncoupled VSV System will help to improve compressor matching at off-design. This accounts for the fact that new aero engines tend to have smaller core sizes with simultaneously rising bleed mass flow requirements.

Methods & Software

The investigations are based on performance calculations in order to assess the effect of a change in VSV control on total engine performance. For a more detailed analysis of compressor performance a compressor mean line tool will be employed.

Optimization of secondary air system flows in different operating conditions

The enhancement of thermal efficiency of gas turbines comes along with an increase of turbine entry temperature. This trend demands both high efficient cooling of turbine discs and blades and sealing of the internal disc space against hot gas ingestion from the annulus. These cooling and sealing mass flows are provided by the secondary air system (SAS). Due to the fact that these flows are taken from the compressor after performing work to the fluid and hence are extracted from the primary cycle, the SAS causes losses in the whole engine's efficiency.

The requirements for secondary air system flow distribution are changing within the engine's operational range as well as the mass flows, set by the air system's elements. Consequently the typically fixed, inflexible air system is designed for worst-case conditions, in order to guarantee engine's safety at every operating point by providing a sufficient amount of cooling and sealing air. Thus mass flows exceed the requirements considerable in a far scope of the operational range which results in significant efficiency losses.

Objective

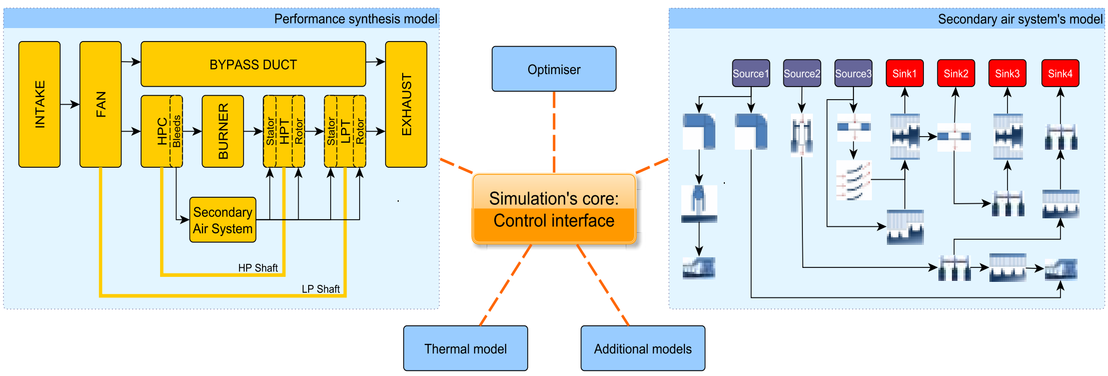
This project is funded by the Bundesministerium für Wirtschaft und Technologie and Rolls-Royce Deutschland Ltd & Co.KG as industrial partner and part of the sub-project cooling of COORETEC – AG TURBO 2020. The aim is the development of a method, which allows an estimation of the impact of variable secondary air flows on whole engine's behaviour. Considering this as the elementary design tool of a flexible SAS, a simulation environment is to be established which optimizes secondary air flows in each operating point. Therefore a multidisciplinary procedure is necessary that particularly deals with the influences on the thermodynamic cycle as well as with the critical requirements of cooled parts like turbine blades, discs and bearing chambers.

engine's efficiency and impact on the lifetime of cooled parts. In a further working stage the framed concepts for a variable secondary air system will be investigated on their technical feasibility. For this purpose the simulation will be extended by characteristics of self-regulating flow-elements, so-called fluidics.

Methods & Software

The used coupled model represents a state of the art civil aero engine which is in the portfolio of Rolls-Royce. Previous to the studies the performance and SAS models as well as the coupled model have to be set up and validated with available test data. The engine's synthesis model will be set up using the performance tool GTlab. Pertaining to the secondary air system's simulation the commercial 1D-CFD tool Flowmaster

AGTURBO
Gefördert durch:
Bundesministerium für Wirtschaft und Technologie
Rolls-Royce



Interface for Performance Synthesis Model and Secondary Air System's Model

Basis & Procedure

As an initial point the connection of an exemplary engine's thermodynamic synthesis model with the detailed 1D model of the associated secondary air system is crucial. With this coupled model, studies on series of defined operating points (design point, full load, partial load, safety-critical points) are conducted to identify possibilities to reduce secondary air flows and hence optimize extraction and distribution of secondary air. Thereby the critical requirements are acting as supreme constraints. Resulting designs and extracted findings will then be evluated with regard to their impact on the whole engine's behaviour, e.g. change of whole

is applied. The conjunction of performance synthesis, secondary air system, optimizer and any further necessary models will be controlled by the core of the aimed method - a newly designed interface.

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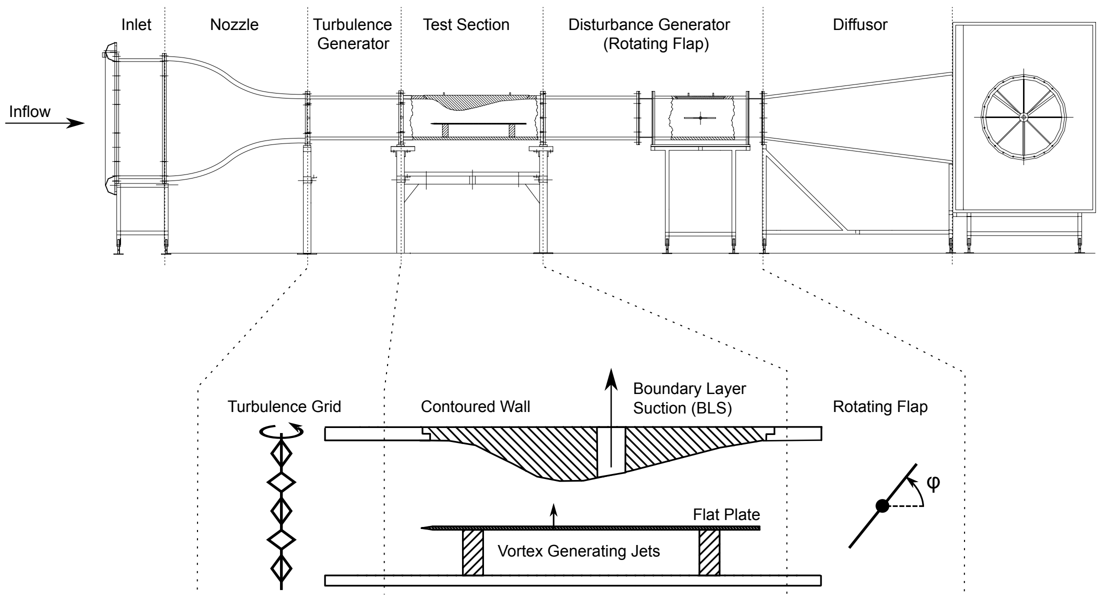
Low Speed Unsteady Wind Tunnel

The Eiffel-type wind tunnel is used for transition and turbulence research. Its modular configuration makes it suitable for various scenarios. It is currently used for low pressure turbine transition research under unsteady main flow conditions.



Wind Tunnel and Test Section Drawing

The flow in turbomachinery components is influenced by many effects. It is highly unsteady due to the wakes generated by the upstream blade rows. These wakes are characterized by a velocity defect and a high turbulence level.

Most of the blade losses in turbomachinery are generated by the flow on the blades' suction side. Maintaining high turning angles with low pressure losses is therefore a challenge for design engineers.

Large-Scale, 2D experiments are necessary to investigate suction side flow and transition phenomena.

These data can be used to evaluate and develop CFD transition models, providing the design engineers with validated tools.

Test Facility	
Square cross section	0.4 m x 0.4 m
Length	1.5 m
Turbulence level	0.3 - 15 %
Mean flow speed	0 - 50 m/s
Velocity fluctuations	0 - 25 Hz
Relative amplitude	0 - 75% of the mean flow
Boundary layer and inflow traverse	

Various turbomachinery conditions can be adapted with turbulence grids, a rotating flap or Vortex Generating Jets. A flat plate is exposed to a pressure distribution by a contoured opposite wall, as seen in the test section drawing. The upper wall is equipped with boundary layer suction to prevent separation.

This simple setup provides excellent access to the test section for flow visualization and optical measurement techniques like Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA).

Due to the very high time resolution hot-wire anemometry is still of great importance in turbulence research to determine for example turbulence length scales, intermittency factors or Reynolds stresses. PIV on the other hand has the ability to record the velocity vectors of a whole flow field and enables for example the calculation of the vorticity distribution. It therefore perfectly complements hot-wire anemometry.

DFG

Hot Wire Measurement

Low-Pressure Turbine Research

In turbofan engines the fan is driven by a low pressure turbine. As the fan produces more than 80% of the engine thrust, the efficiency of the low pressure turbine is of crucial importance for the specific fuel consumption of the engine. At the same time the turbine contributes 30% to the engine weight.

As typical efficiencies are already above 90%, an overall efficiency increase is aimed to be achieved by reducing the blade count, while maintaining high efficiency levels. This would decrease the weight and therefore fuel consumption as well as maintenance costs.

These considerations lead to the design of High-Lift and Ultra-High-Lift bladings. Laminar separation bubbles are accepted in this design, as long as they are thin and the turbulent boundary layer attaches reliably before the trailing edge. The wakes shed from the upstream blade rows and the increased turbulence level contribute to the effectiveness of this design, as they force transition and therefore reduce the time averaged separation bubble size.

Unsteady Main Flow

The blade wakes are characterized by an increased turbulence level and a velocity defect. For a detailed understanding it is necessary to investigate these effects separately. The rotating flap of the wind tunnel produces a sinusoidal-like inflow to the test section without affecting the turbulence level. This simulates the velocity defects of blade wakes. The frequency of the unsteadiness can be controlled by the rotational speed of the flap, while flaps of different sizes produce different amplitudes. The maximum achievable frequency is 25 Hz while the maximum relative amplitude is 75% of the mean flow velocity.

Turbulence

The turbulence level can be increased up to 7% by employing static turbulence grids. An active turbulence grid with independently, randomly forced rotating vanes, can produce turbulence levels up to 15%. Furthermore it allows exciting discrete frequency ranges of the turbulence spectra.

Active Flow Control

The flat plate is equipped with Vortex Generating Jets. Their position can be shifted in a range of stations upstream of the flat plate suction peak. Pulsed and continuous operation allows triggering transition and decreasing the separation bubble size to reduce the suction side losses.

Stereo Particle Image Velocimetry

2x PCO 4000 (11Mpx)
Litron Laser (200 mJ pulse energy)
Various Lenses

Current Activities

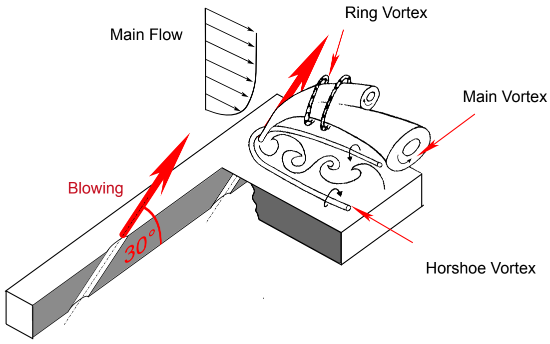
Currently two DFG funded projects use the test setup of the Low Speed Unsteady Wind Tunnel. In these projects, the unsteady main flow conditions are either combined with the Vortex Generating Jets or the various turbulence generation methods.

One project investigates the influence of steady and pulsed Active Flow Control through Vortex Generating Jets in steady and unsteady main flow on separated flow transition. The aim is to clarify how they affect the boundary layer as well as analyzing their capability to increase the efficiency of low-pressure turbines.

Current Test Configuration	
Re	80.000 - 300.000
Sr	0.5 - 2
Plate length	1 m
Pressure dristribution	0.8 m, LPT Pak-B

The Vortex Generating Jets induce a vortex pair. The strong vortex perpendicular to the flow, transports low-energy fluid from the boundary layer into the main flow and vice versa.

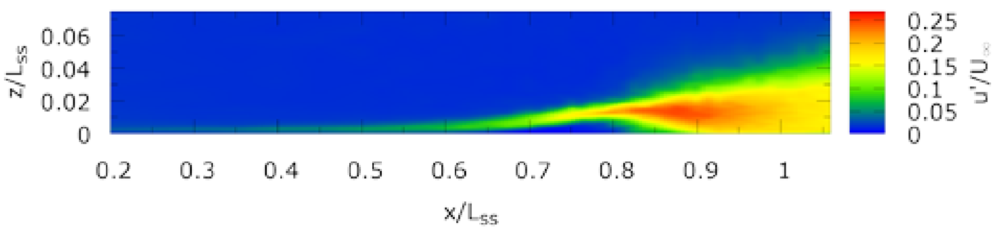
Detailed measurements show, that the blowing speed influences the induced vorticity and the interaction between the boundary layer and the vortices. A change in the blowing position around the suction peak of the low pressure turbine pressure distribution gives an idea about the intensity of the vortex structures at certain positions depending on the velocity gradients. As a result, an optimal position of the vortex generating jet blowing can be determined. Pulsed activation of the flow leads to a calmed zone in the flow that reduces the profile losses significantly for a period of time. The pulse width of the blowing plays an important role in the transition process.



Vortex Generating Jets

- Flexible duty cycle 0 - 100 %
- Frequency range 0 - 200 Hz
- Blowing ratio 1 - 5
- Variable actuator position 0.38 - 0.53 x/l
- Jet angle: 30° to plate surface, 90° to main flow

The aim of the project is to identify the vortex structures and the effect on transition under unsteady main flow conditions with different blowing speeds, different blowing ratios and amplitudes. Also the main flow speed is varied under different fluctuation frequencies and amplitudes. As a result, the effects of blowing ratio, blowing position and duty cycle change the behavior of separation and flow transition, and thus turbine efficiency.



Separation bubble at increased freestream turbulence level

Active Turbulence Grid

• 16 independently rotating axes
• Turbulence intensity up to 15% of mean flow
• Various random forcing mechanisms

The second project investigates the influence of high turbulence levels and the characteristics of the turbulence spectrum on the transition process in steady and unsteady main flow.

High freestream turbulence affects the laminar boundary layer. The shear sheltering effect damps the high frequency content of the freestream turbulence spectrum while amplifying the low frequency content. Although the laminar profile is preserved, these phenomenon lead to higher turbulence intensities in the boundary layer than in the freestream. Laminar streaks develop, which are zones of higher and lower velocity than the average. The shear stress between these streaks is believed to be the transition trigger. The time mean representation of this effect is called Klebanoff Modes. They affect the momentum transport and therefore influence the ability of the boundary layer to withstand adverse pressure gradients. The transition onset is shifted to smaller Reynolds numbers, while the transition length is increased. Separation bubbles might still occur, but they are in general thinner and shorter.

The figure on the bottom of the left page shows the turbulence intensity of the boundary layer in the presence of a separation bubble. The increased turbulence intensity in the laminar boundary layer prior to separation ($x/L_{ss} < 0.65$) is visible. The aim of this project is to identify the properties of laminar streaks and how they are affected by the turbulence level, integral length scale and ratio of anisotropy.

Measurements show that if the nominal longitudinal turbulence level is held constant, the turbulence length scales determine the size of the separation bubble. At very high turbulence levels the length scales can determine whether a separation is present or not. Single and X-Hotwire anemometry is used to determine the turbulence spectrum and characteristic frequency in the shear layer. The ability of Particle Image Velocimetry (PIV) to give a complete view of the flowfield makes it possible to capture the laminar streaks and measure their properties like velocity and dimension, which has never been done before. The influence of unsteady main flow on this process will also be investigated in later stages of the project.

Publications (Selected list)

Dähnert, J. , Lyko, C. and Peitsch D.Transition Mechanisms in Laminar Separated Flow Under Simulated Low Pressure Turbine Aerofoil Conditions. Journal of Turbomachinery 135 (January 2013), pp. 011007–1 – 011007–10.

Lyko, C., Dähnert, J. and Peitsch, D. Forcing of Separation Bubbles by Main Flow Unsteadiness or Pulsed Vortex Generating Jets - A Comparison. Proceeding of the ASME Turbo Expo 2013, San Antonio, Texas, USA, June 3.–7., 2013, GT2013-94575.

Lyko, C., Dähnert, J. and Peitsch, D. Transition Mechanisms in Laminar Separated Flow under Unsteady Main Flow Conditions - Part I: Steady Flowfield. Proceeding of the International Gas Turbine Congress 2011, Osaka, Japan, November 13-18, 2011, IGTC2011-0254.

Lyko, C., Dähnert, J. and Peitsch, D. Transition Mechanisms in Laminar Separated Flow under Unsteady Main Flow Conditions - Part II: Unsteady Flowfield. Proceeding of the International Gas Turbine Congress 2011, Osaka, Japan, November 13-18, 2011, IGTC2011-0255.

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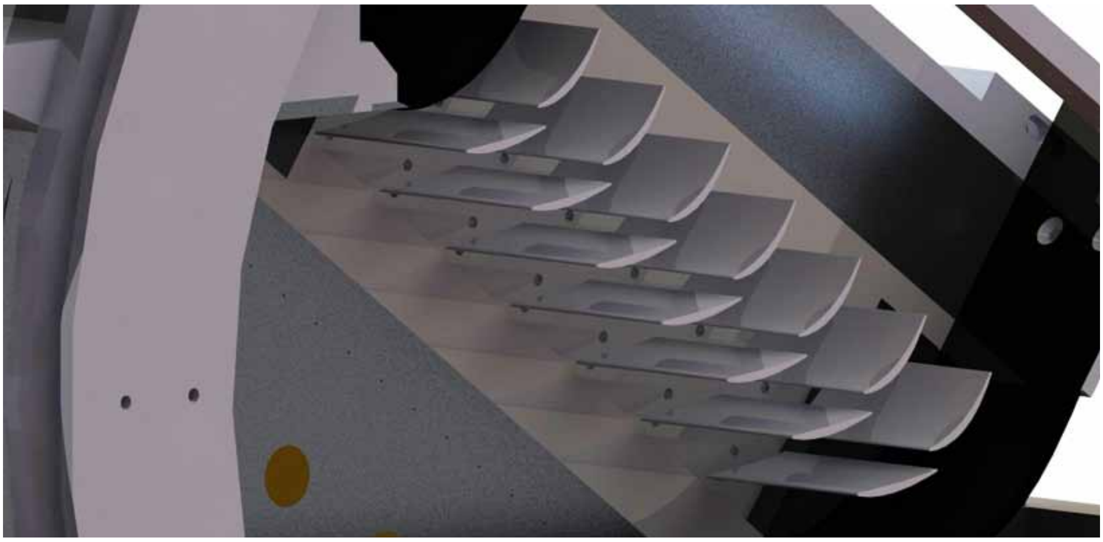
High Speed Wind Tunnels

The linear high speed tunnel is used for active flow control and tandem blade investigations. Rotating Instability is examined at the annular high speed test rig.



Linear High Speed Cascade

Linear High Speed Compressor Stator Cascade for Active Flow Control Investigations (AFC)

Aircraft manufacturers and airlines demand for highly efficient engines to address the more and more stringent requirements in terms of economy and environmental compatibility. This target requires light and compact propulsion systems, leading to the necessity to reduce the weight of the single components. Within the compressor module, the number of the required stages can be minimized by a higher stage pressure ratio at constant total pressure ratio.

This can be done by a stronger deflection of the flow within the passage of a supercritical compressor blade. Nevertheless, separation needs to be avoided, one approach being active flow control.

Geometric parameters	
Profile	CDA
Chord	80 mm
Blade Aspect ratio	0.8
Pitch-to-chord	0.5
Thickness ratio	0.06
Stagger angle	20 deg
Deflection angle	55 deg

Active flow control has been intensively investigated at the chair of aero engines within the transfer project T7 of the research cluster SFB557.

As a basis for the development of a closed-loop active flow control method, a detailed investigation of the flow field without actuation is necessary. Steady and pulsed blowing through a side wall slot to minimize separation in a compressor cascade is investigated as well.

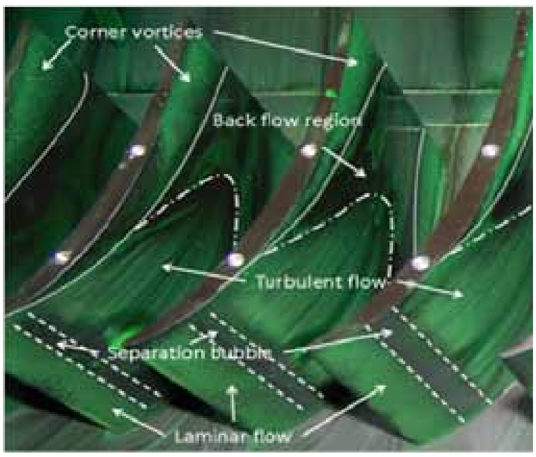
For the experiments 2D controlled diffusion airfoils are used with a small blade aspect ratio. The table lists the design parameters of the compressor cascade. The blade features an elliptical leading edge.

Five-hole probes are used to determine the pressure field and the flow direction of the wake downstream of the compressor blade. Furthermore an analysis of the baseline cascade flow by oil flow pattern reveals complex three dimensional secondary flow phenomena. On the suction side of the blades, close to the leading edge, a laminar separation bubble can be observed. Where blade and side walls meet, corner stall is developing. Due to the small blade aspect ratio the passage flow is strongly influenced by these vortices. Uniform main passage flow is thus constricted to the midspan region, leading to a reduction of the passage efficiency. The experiments show how the secondary flow phenomena can be suppressed by active flow control methods to receive a higher stage pressure ratio or lower total pressure losses respectively and where the limits of these methods are.

For this purpose, actuators for steady and pulsed blowing through a side wall slit were developed. For closed-loop control, the middle blade is replaced by a blade equipped with 16 high resolution pressure sensors.

To ensure high flexibility the injection nozzle is a replaceable component which is inserted into both the side wall and the blade root. Compressed air is routed through small tubes to the nozzle exit. The injection angle is fixed to 20 deg between the nozzle exit plane and the side wall, thus leading to an elliptical exit geometry of the nozzle.

The injected air is inserted tangentially to the blade surface at the blowing position of 10% chordlength. Pressurized air is provided by a radial compressor and led through a mass flow meter into two small pressure tanks. From the pressure tanks the air is then directed through electro-magnetic valves into the nozzles. To ensure uniform flow conditions each passage features an actuator at each side wall. In total 16 actuators are needed. The injection amplitude is controlled by a pressure control valve for each pressure tank. To achieve secure operation and enhancement of the performance of axial compressors for aerodynamically highly loaded blade profiles even under disturbed conditions, the magnitude of the actuation needs to be adjusted by a closed-loop controller.



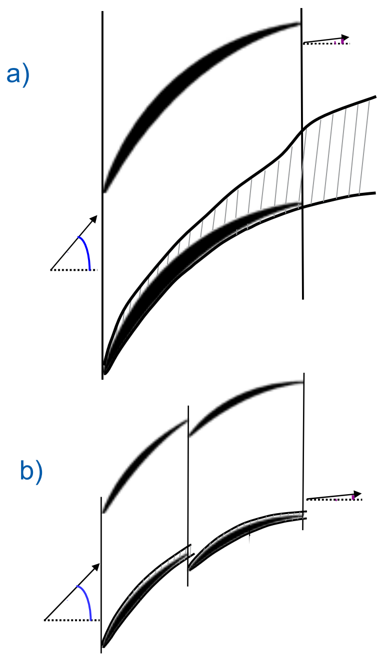
Oil Flow Visualization (baseflow)

Tandem Blades (TB)

Tandem stators are investigated at the linear high speed cascade as well. They are an interesting approach to increase the stage pressure ratio by avoiding separation.

Conventional blade designs achieve higher stage pressure ratios with an increased turning of the flow limited by the increased risk of separation.

Therefore, modern compressor design engineering focuses on new blade designs to prevent separation while retaining the higher turning of the flow. For tandem blades, the flow deflection is now realized by two blades positioned directly one after another. As a result the critical blade loading is split onto two blades allowing a higher pressure rise but also a more stabilized flow guidance thus reducing the risk of flow separation. The figures of the tandem blades visualize the reduced bound-



a) Conventional Blade b) Tandem Blade
c.f. Mc Glumphy

ary layer development due to the shortened chord length and the optimized flow guidance.

The objective of the project is to develop validated computational approaches to support the early design phase of compressor modules with large deflection angles and to get detailed information about the influence of the secondary flow structures on the blade performance.

This is supported by both experimental and numerical investigations. In the course of this project four different configurations for 35° and 50° deflection angle and two different Lift Split (LS) variations are compared against conventional single CDA blades. In order to get a full understanding of the secondary flow development and in particular of the influence of the stagnation point on the sidewall characteristics, both the axial and tangential pitch can be varied as well as the oncoming boundary layer thickness.

By the use of tandem blades the resulting losses can be reduced or avoided. Therefore the influence of the aerodynamic loading and the boundary layer thickness of the inflow on the blade performance are investigated. The project is carried out in cooperation with the Research Association for Combustion Engines e.V.

Rotating Instability (RI)

In state-of-the-art high-pressure compressors, the performance is limited by aerodynamic instabilities, such as rotating instability (RI), part-span stall and rotating stall (RS). These phenomena typically occur under conditions of high loadings of single blade rows which limit the performance of the whole compressor system.

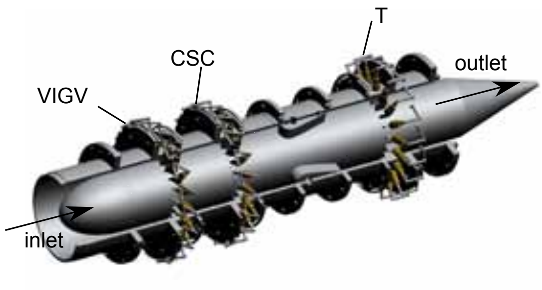
Geometric parameters	
Profile	CDA
Chord	34 mm
Blade height-chord ratio	1
Pitch-to-chord	0.95
Max.thickness chord-ratio	0.08
Stagger angle	25 deg
Camber angle	30 deg

The highest pressure ratios allowing high efficiencies of the whole engine are achieved in the vicinity of the stability line. To ensure stable operation of the compressor system, a safety margin to the stability line has to be maintained which thereby limits the achievable pressure ratio and thus high efficiencies.

The causing mechanism of the RI is still not fully understood. Therefore, the goal of the project is to get a profound understanding of RI by parallel adaption of different measurement techniques.

Description of test facility

The experimental investigations are carried out on an annular compressor stator cascade. The test rig itself consists of three

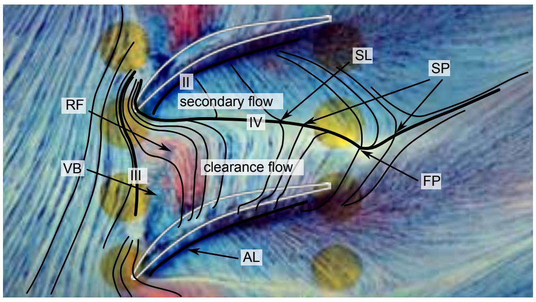


Annular Compressor Test Rig

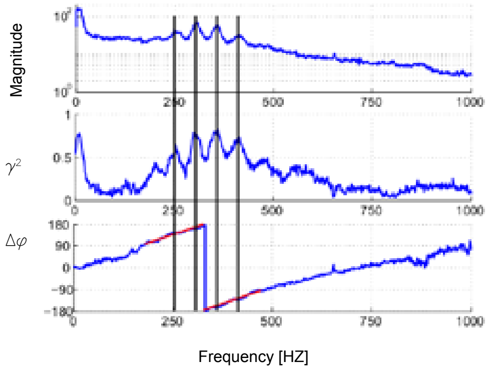
separate blade rows, namely a Variable Inlet Guide Vane (VIGV), the compressor stator cascade (CSC) and a throttle (T). The incidence of the compressor blades inflow is adjusted by changing the stagger angle of the VIGV, whereas the throttle is used to adjust the aerodynamic parameters within the test rig. The compressor stator cascade itself consists of 20 prismatically shaped blades which are very sensitive to flow separation and similar to a controlled diffusion airfoil (CDA). The parameters of the profile are shown in the table.

Description of measurement techniques

To investigate the RI on the compressor stator cascade different measurement techniques are used. Steady flow field measurements are conducted with five-hole probes upstream of the compressor cascade leading edge and downstream of the trailing edge. To track the secondary flow structure at the hub endwall and as well at the pressure and suction surface of the blades, multi color oil flow visualization is carried out at specific operating points.



Oil Flow Visualization Streamlines
with detected RI



Characteristic Frequency Pattern of RI

The time resolved measurements were performed using piezoresistive pressure transducers at the hub upstream, downstream and inside of a compressor stator passage. To obtain not only the time resolved endwall flow structure but also the time resolved flow field within a whole passage, hot wire measurements of a complete passage were performed.

The aim of this project is to get a comprehensive picture of the passage flow and the flow phenomena with increasing aerodynamic loading in regard to the inception of RI.

In previous studies it was shown that the rotating instability occurs not even at different radial gaps but even without any gap. From this result the theory of the formation mechanism by the clearance vortex needs to be reconsidered. Moreover it was shown that the aerodynamic loading is the critical parameter for the inception of the RI and the characteristic frequencies of the RI are directly related to the inflow Mach number.

The flow visualization results at operating points with detected RI show a reverse flow out of the passage around the blade leading edge of the adjacent blade which was related to the RI.

Furthermore, it was shown by experimental results that the RI has a direct influence on the performance characteristic of the compressor stator cascade. Thus, the rotating instability must not only be taken into account from a structural and acoustic point of view but also in terms of performance and efficiency.

This project is part of the collaborative research project “Flow induced acoustics in turbomachinery – The rotating instability” funded by the German Research Foundation (DFG).

Publications (Selected list)

Beselt, C., Peitsch, D., van Rennings, R., Thiele, F. Impact of hub clearance on endwall flow in a highly loaded axial compressor stator. ASME Turbo Expo 2013 San Antonio, Texas, USA, June 3.–7., 2013, GT2013-95463.

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C. Tiedemann, A. Heinrich, D. Peitsch. A new linear high speed compressor stator cascade for active flow control investigations. 6th AIAA Flow Control Conference, New Orleans, USA, June 25-28 2012, AIAA-2012-3251

C. Tiedemann, S. Steinberg, D. Peitsch, King R.. Identifikation einer Regelgröße zur aktiven Strömungskontrolle an einer linearen Verdichterkaskade im kompressiblen Machzahlbereich, Deutscher Luft- und Raumfahrtkongress 2012, Berlin, Germany, September 10-12 2012, DLRK-2012-281267

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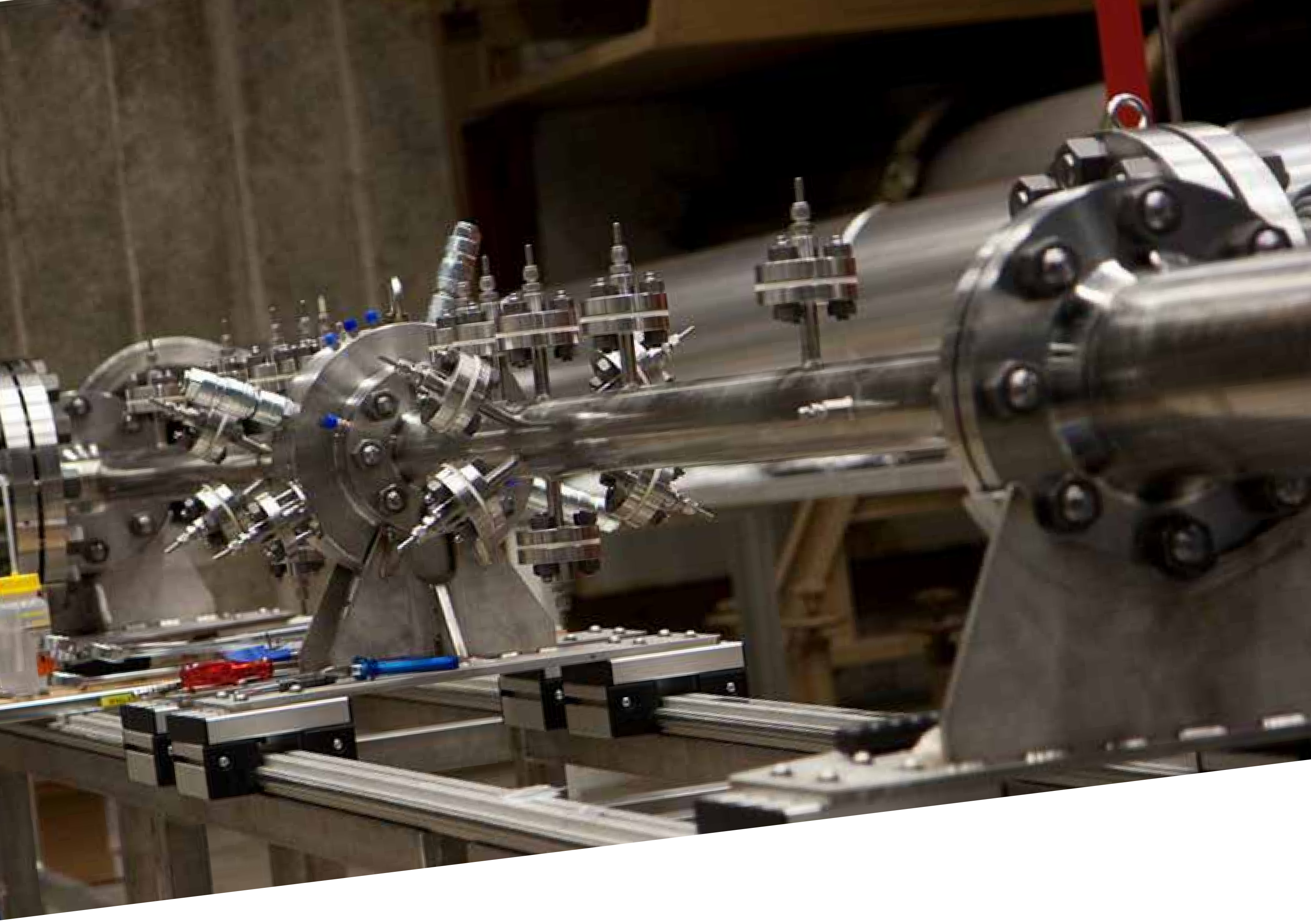


Hot Acoustic Testrig (HAT)

In order to increase the efficiency of gas turbines and aero engines the Collaborative Research Centre (SFB) 1029, founded by DFG examines coupled unsteady combustion and flow dynamics.

The major contribution to such an efficiency increase is expected from a thermodynamically motivated move from a constant-pressure to a constant-volume combustion.

This results in periodically changing pressures downstream of the compressor and upstream of the turbine. This has severe consequences with respect to a stable operation of the compressor or a reliable cooling of the first stages of a turbine.

To control these implications flow control methods either passive or in closed loop will be applied.

These flow control methods will be built up in such a fashion that they offer an additional increase in efficiency which can even be used in a classical gas turbine as well.

The HAT is used to investigate the impact of changing pressure in the high pressure turbine.

Objective

To prevent the hot gas flow after the combustion chamber from penetrating into the sensible inner area of the engine it is necessary to establish a sealing between rotating and stationary parts. In turbomachinery such a sealing is provided by a cooler secondary air stream blowing into the rotor-stator-cavity of the high pressure turbine. The purpose of this project is to investigate the sealing cavity under the conditions of the unsteady combustion, in order to prevent hot gas ingestion into the inner turbine. The main aim is to find a new geometry for the cavity while decreasing the secondary airflow needed for the sealing.

Setup Hot Acoustic Testrig	
Cross section	0.045 m x 0.09 m
Ma	0 - 0.6
Temperature	770 K
Seondary air	Δp < 3 bar

Methods and Test Rigs

In the beginning the experiments will be performed in a double stream wind tunnel under atmospheric conditions. They concentrate on the interaction between the leakage flow and the main gas flow and in particular on the influence of different rim seal geometries. One flow path serves as the main stream and the other as the sealing flow, while both are mixing out at the designed cavity. Starting with investigations under steady state conditions, it is possible to provide an unsteady flow in one flow path of the wind tunnel.

This large scale setup provides a perfect access for various measurement techniques and the possibility of a quick adjustment of the experimental setup. Optical Methods such as Particle Image Velocimetry (PIV) as well as Hotwire anemometry and pressure probes can be used to investigate the main flow/sealing air interactions visible in the typical alternating pressure distribution around the rotor-stator-cavity.

Based on these investigations, further studies under more realistic flow conditions are performed in the Hot-Acoustic-Testrig.

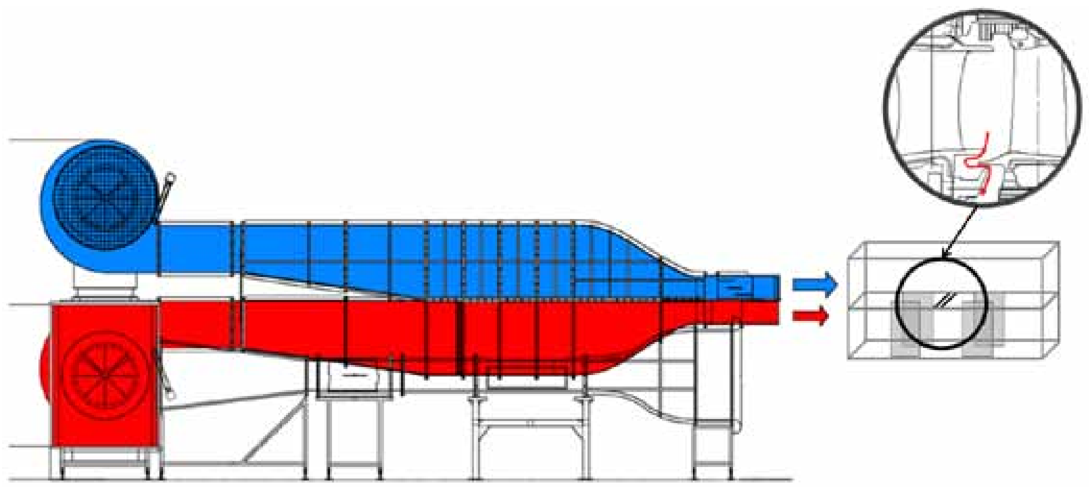
For testing, a significant difference in temperature between main gas flow and leakage mass flow is considered and the variation of the differential pressure is realized. For this purpose a pressured plenum is attached to the rectangular test section to provide the cooler sealing flow into the hot gas. In these tests new geometries in respect of their sealing efficiency are examined. The windows consist of quartz glass allowing optical measurements technique (PIV).

Outlook

In a next step a technique to generate an unsteady main flow for the Hot-Acoustic-Testrig is required to investigate the cavity under the conditions of the pulsed combustion. New methods e.g. Pressure Sensitive Paint (PSP) and Temperature Sensitive Paint (TSP) shall be deployed. The results of the project shall be used for further investigation, where the focus will lie on annular or rotating setups.

Setup Double Stream Wind Tunnel

Cross section	2 x 0.3 m x 1 m
Re	< 700.000
Mean flow speed	0 - 40 m/s
Tu	0.3



Double Stream Wind Tunnel

www.sfb1029.tu-berlin.de

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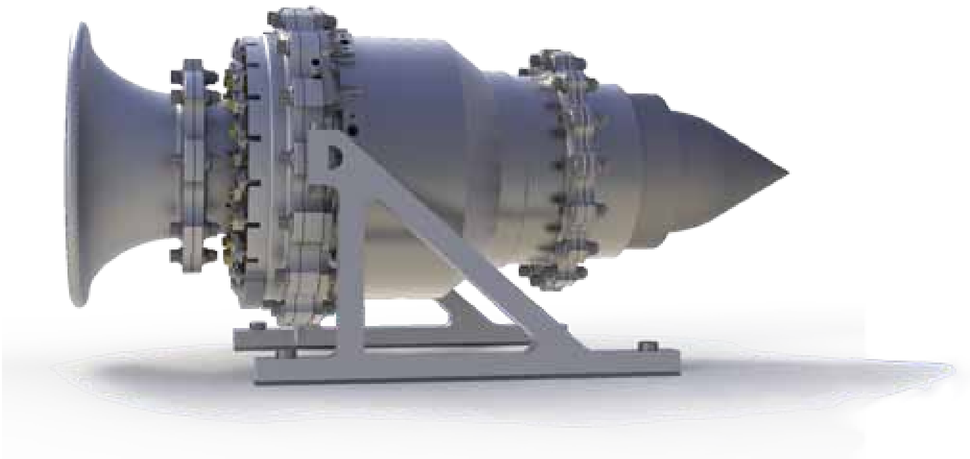
Micro Gas Turbines

The project JETSDREAMS is a student workshop in which a micro gas turbine and a gas turbine for power generation application are developed and built from scratch.



JETSDREAMS

„**J**et **E**ngine **T**est **S**tand for **D**ata **R**ecording, **E**valuating **A**nd **M**onitoring for **S**tudents Education“

Within the project “JETSDREAMS” students are engaged in the design, manufacturing and operation of micro gas turbines. In previous project phases, two micro gas turbines have been developed (KGT 200 and CO_2NCEPT) which are continuously developed further in order to optimize engine operation.

Target application areas are for example decentralized energy production, as well as range extenders for electric cars.

Due to the increasing oil price development it seems sensible to look for alternative fuels as well. It is therefore one of the project‘s targets to investigate engine performance using alternative combustibles. This includes the assessment of the emissions in order to find an answer to the question of what is the most valuable fuel of the future.

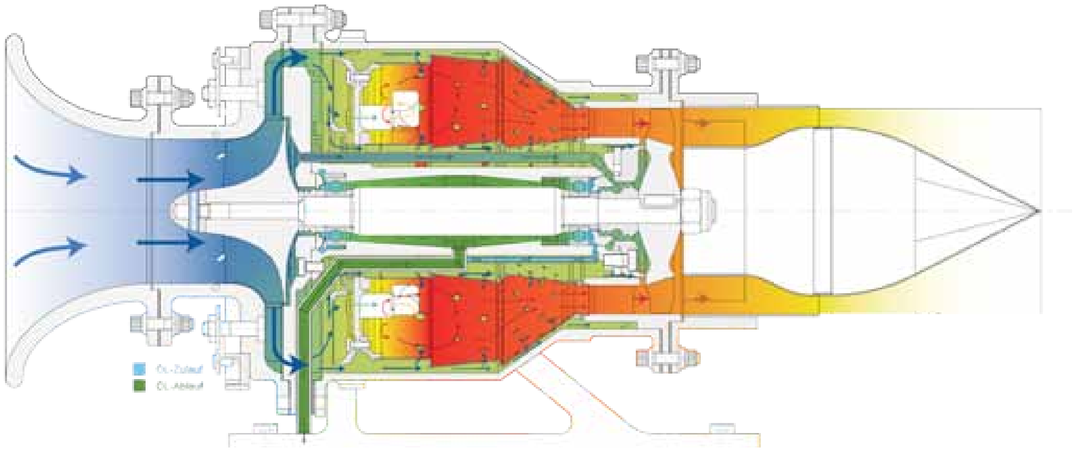
KGT 200

The KGT 200 is a thrust producing one shaft micro gas turbine employing a radial compressor in conjunction with a single stage axial turbine. As well as its predecessor machine (KGT 100) it was completely self-developed and built by students.

After the first testing phase an optimization process was started with a focus on optimization of the combustion chamber and the bearing chamber. This includes a complete self-designed oil and air system. Subsequent tests have shown that the redesigned components and systems are workin gas expected.

Further steps in the development process will include a complete performance calculation as well as CFD-Simulations in order to digitally map the engine’s performance. This in return supports the optimization of the engine components.

The project offers the students an optimal practical possibility to apply the imparted knowledge from the lectures.



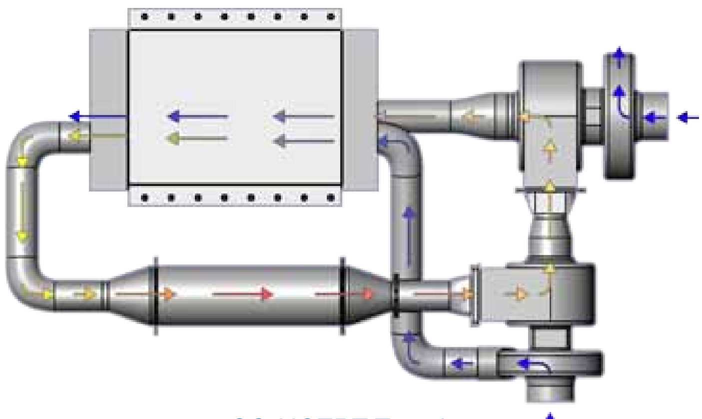
KGT 200 cross section

CO_2NCEPT

The „CO_2-Neutral, Compact, Electric Power Turbine“ (CO_2NCEPT) is a gas turbine for power generation. It consists of two turbochargers, a combustion chamber and a heat exchanger. The resulting power of 20kW is tapped from the second turbocharger by using a generator. CO_2NCEPT was built from existing components provided by automotive industry. The aim was to establish a low cost but robust gas turbine cycle which produces power by combining given components. The approach is different to the KGT 200 where the focus is on the design and construction of the single components.

The very modular design allows a replacement of individual parts in order to analyze different components. Especially combustion chamber configurations as well as alternative fuels can be tested. Therefore CO_2NCEPT serves as test vehicle for micro gas turbine components.

The project helps to promote the sustainability because an electricity generation with alternative fuel can be easily examined. Besides generating electricity, this CO_2NCEPTcan be employed to extend the range of hybrid vehicles.



CO_2NCEPT Test rig

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Aeroelasticity

The Chair of Aero Engine is setting up an aeroelastic test rig which was previously placed at the DLR Institute of Aeroelasticity in Göttingen.

The facility allows controlled flutter and forced response testing. It is an open circuit wind tunnel, exhausting to ambient condition. The air supply of 75 kW power delivers 15 kg/s cold air maximum. The test section is made up of a linear cascade of eleven carbon compressor blades of the NACA serie 65. Nine blades are elastically mounted and two blades are fixed at the inner and outer wall.

Elastic mounting of the blade

The elastic mounting allows free oscillation in the orthogonal bending and torsion rigid-body modes and a mode coupling. The blades can individually be exaggerated to oscillate in a bending and torsion rigid-body mode by an electric drive. The complete test section can be optically accessed, opening up the possibility of using optical measurement techniques.

The instrumentation of the facility will comprise of steady-state and unsteady measurement devices. The devices will be used to determine the mean flow condition and the unsteady pressure fluctuations on the blades‘ surfaces. The mountings are instrumented with strain gauges in order to measure the aeroelastic eigenfrequencies. PIV measurements can also be performed. The test module provides high flexibility regarding setup modifications, thus the blades can be easily changed. The intention is to investigate flutter of turbomachinery blading for various velocities and profile designs. In particular the aerodynamic coupling will be investigated which addresses the new challenges resulting from the design trend towards lighter blades.

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