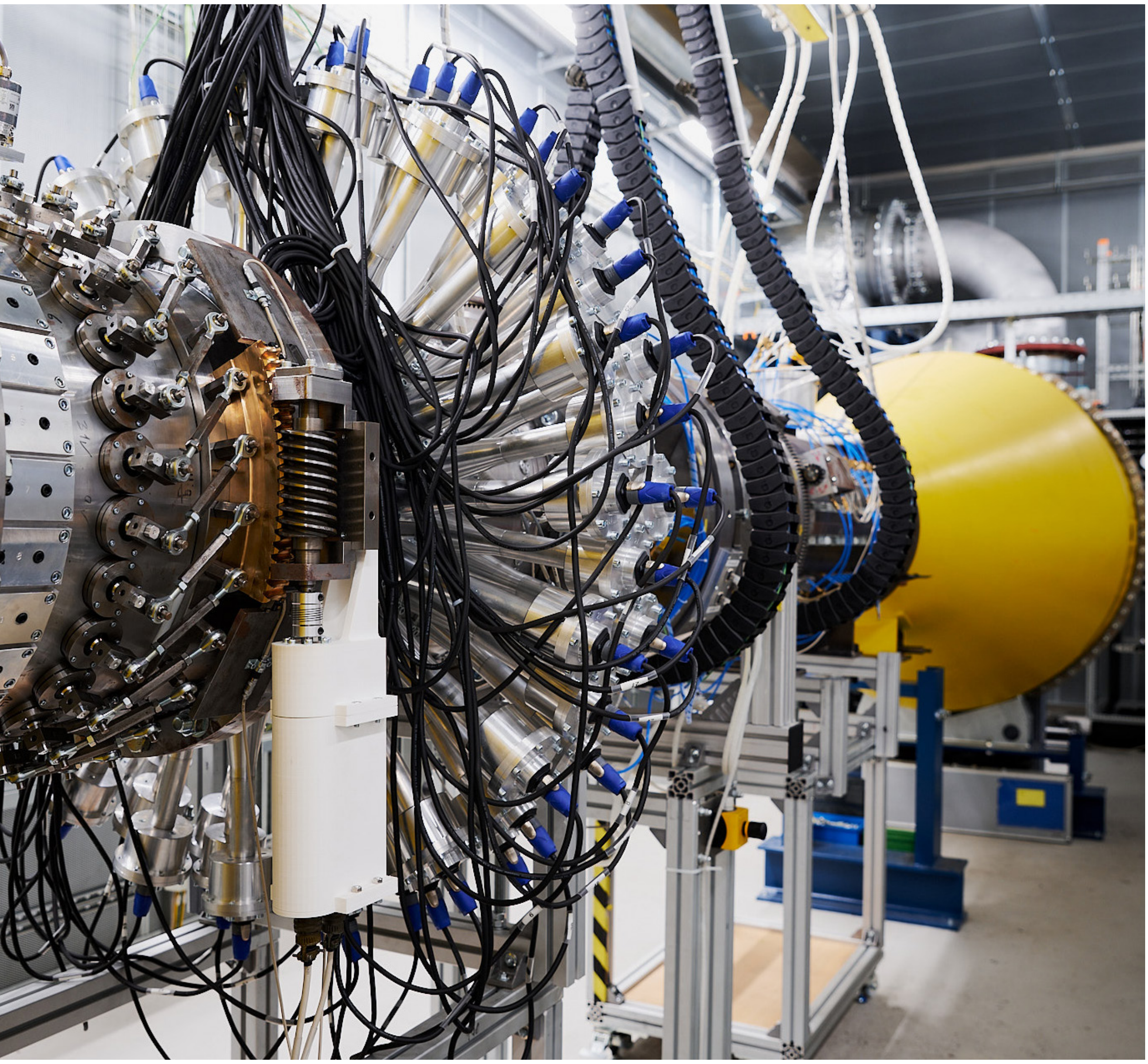
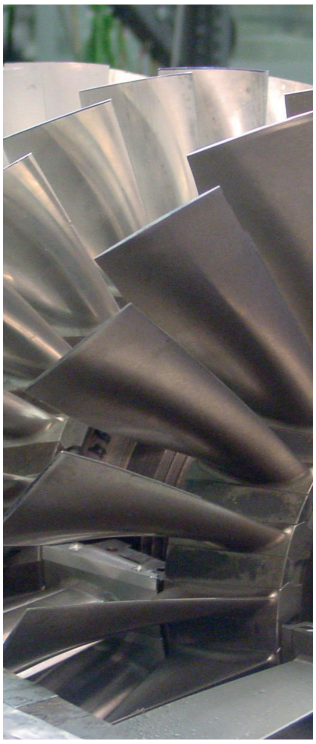
Institute of Turbomachinery
and Fluid Dynamics

Leibniz
Universität
Hannover

Institute of Turbomachinery and Fluid Dynamics





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Four-stage high speed axial turbine

© Sören Pinsdorf

Who We Are

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Welcoming Remarks

Are you looking for a reliable partner to improve your products? We offer a wide range of services – short term consulting projects, manufacturing and instrumentation, analytical, testing, FEM and CFD services, and long term research projects.

Our ambition and competitiveness is proven by our continuous relationships with partners in industry, resulting in us becoming MTU's partner in their Centre of Competence for turbine technology. Personally, I bring to such collaboration 30 years of experience with turbomachinery in both, industry and academia.

We are experts in multidisciplinary design, as was shown by the design, manufacture, and test of a 10kW ORC supersonic turbine generator. For this success, we were honoured with the German Steel Innovation Award 2018. Our publications were recognized with a Best Technical Paper Award of the Institute of Mechanical Engineers'[1] and Best Paper Awards at the ASME Turbo Expo[2]. The excellence of our research helped us to lead the Collaborative Research Centres (CRC) 871 "Product-Regeneration", contribute to the CRC 880 "Fundamentals of High Lift for Future Civil Aircraft", and the Cluster of Excellence SE^2A "Sustainable and Energy-Efficient Aviation".

Join us on our way to shape the future through innovation in turbomachinery for sustainable energy and transportation.

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1 **Shaaban, S.; Seume, J.R. (2006):** Analysis of Turbochargers Non-Adiabatic Performance, Proceedings of 8th International Conference on Turbochargers and Turbocharging (IMechE), 17-18 May 2006, London, UK, C647/027

2 **Schinnerl, M.; Ehrhard, J.; Bogner, M.; Seume, J.R. (2017):** Correcting Turbocharger Performance Measurements for Heat Transfer and Friction, Proceedings of the ASME Turbo Expo 2017, 26-30 June 2017, Charlotte, NC, USA, GT2017-64283, **subsequently published in ASME** J. Eng. Gas Turbines Power 140(2), 022301 (Oct 03, 2017) (9 pages)
Fischer, T.; Burgmann, S.; Rudersdorf, M.; Seume, J.R. (2017): Partially Vaned Diffuser With Variable Cross-Section for Centrifugal Fans, Proceedings of ASME Turbo Expo 2017, June 26-30, 2017, Charlotte, NC, USA, GT2017-63965

www.tfd.uni-hannover.de/en

New mechanical engineering campus 2020

Gottfried Wilhelm Leibniz Universität Hannover (LUH)

Key facts[3]
- More than 27,000 students
- More than 350 professors
- Nearly 3,400 research and teaching staff

The heart of Leibniz University Hannover beats in the idyllic Welfenschloss, the Guelph Palace. The year 1879 saw the Higher Vocational School, originally founded in 1831, move into the palace. Later, the Higher Vocational School became the Royal College of Technology. While 64 pupils first attended the Vocational School, the university now has around 27,000 students. More than 3,000 academics and scientists work at the university in nine faculties with around 160 departments and institutes.

Shaping the Future with Knowledge – as one of the nine leading Institutes of Technology in Germany, Leibniz University is aware of its responsibility in seeking sustainable, peaceful and responsible solutions to the key issues of tomorrow. Our expertise for this stems from the broad spectrum of subjects, ranging from engineering and natural sciences to architecture and environmental planning, from law and economics to social sciences and humanities.[1]

Ethical Science – we act responsibly[2]

Research as a challenge – we aim for the top[2]

Cooperation as a principle – we work as a team[2]

Creating new ideas – we are committed to excellence in teaching and research[2]

1 History and Preamble of the Mission Statement of the LUH
2 Extract from Mission Statement of Gottfried Wilhelm Leibniz University Hannover
3 Extract from Facts and Figures of the LUH

Who we are

Institute of Turbomachinery and Fluid Dynamics (TFD)

We pursue interdisciplinary research within the university's engineering faculties and beyond. To support the personal and professional development of our students and researchers, we have established long-time relations and partnerships with research institutions and industry worldwide.

Key facts

- ➞ 33 doctoral research assistants and 21 technical and administrative staff
- ➞ 10-20 international peer reviewed publications p.a.
- ➞ Access to high-performance clusters with up to 6.05 PFlop/s LINPACK Performance (ranked at 184th place worldwide)

Courses

- ➞ Fluid Dynamics
  - Fluid Mechanics I
  - Fluid Mechanics II
  - Computational Fluid Dynamics
  - Rotor Aerodynamics
  - Flow Measurements and Testing Techniques
  - Aerodynamics of Vehicles
- ➞ Turbomachinery
  - Aerothermodynamics of Turbomachinery
  - Heavy Duty Gas Turbines
  - Aeroacoustics and Aeroelasticity of Turbomachinery
  - Steam Turbines
  - Aircraft Engines
  - Turbochargers

Academic Research Consortia

www.tu-braunschweig.de/en/se2a

SE²A Sustainable and Energy Efficient Aviation

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www.sfb871.uni-hannover.de/en/

Product - Regeneration
Collaborative Research Center 871
Regeneration of Complex Capital Goods

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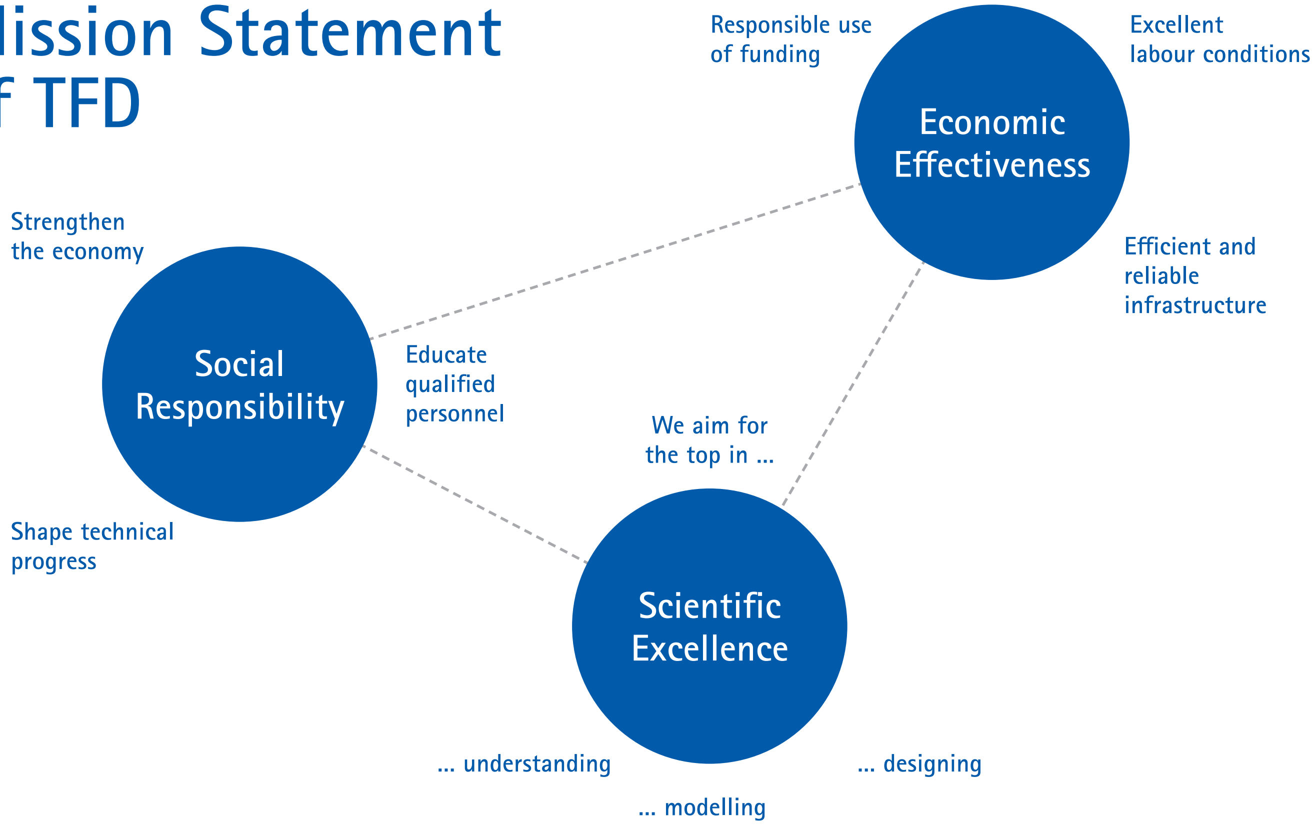
Mission Statement of TFD



Quality Management

We have a Quality Assurance System in place since 2011. It prescribes procedures and processes in the areas of teaching, training, research, and services. The regulations are based upon the requirements of DIN EN ISO 9001 and are laid down in a written document, the Quality Assurance Manual (QAM). The QAM serves to increase customer satisfaction through effective application of the Quality Assurance System described therein. This includes the processes for continuous improvement of the system itself and the assurance of compliance with customer requirements and applicable official requirements. The Quality Assurance System applies to all of our facilities and personnel activities, both at LUH sites and outside LUH sites where we carry out external services. In addition, since December 2024, TFD's workshops are fully certified according to ISO 9001 for all mechanical and electrical products manufactured at TFD.

We have implemented review processes for design and numerical analysis based upon industrial standards to save technical and scientific resources.


TÜVNORD

Certificate

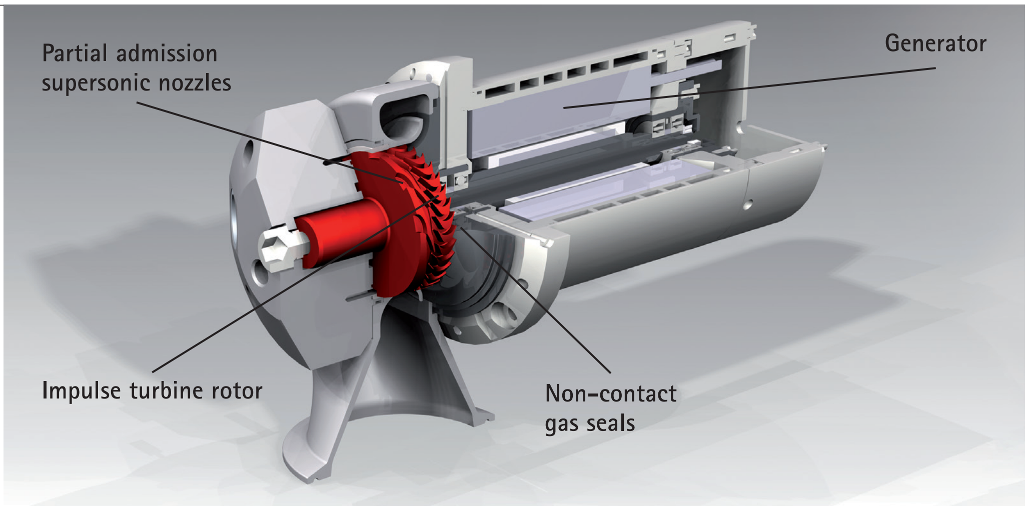
Management system as per
DIN EN ISO 9001:2015

TÜVNORD
TÜV NORD CERT GmbH
DIN EN ISO 9001
tuev-nord.de

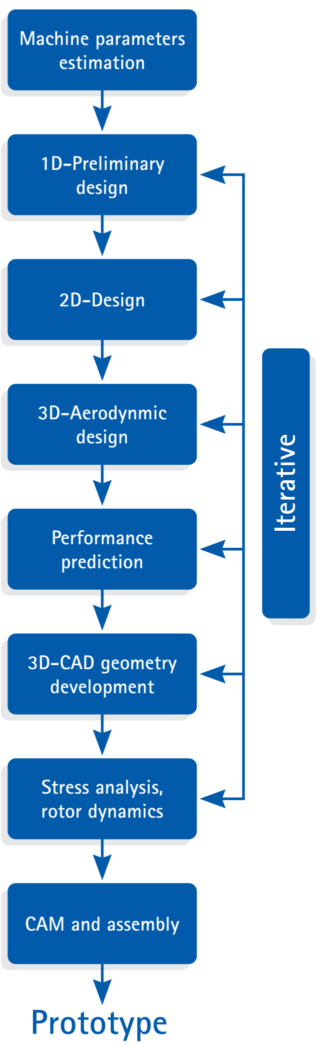
Design & Prototyping

Organic Rankine Cycle (ORC) supersonic turbine generator for energy recovery in trucks – German Steel Innovation Award 2018

http://www.stahl-innovationspreis.de/news/gewinner-2018-effizientere-lkw-motoren-durch-abwaermenutzungsonderpreis/



Workflow



Design of Turbomachinery

We offer the whole design procedure for turbomachinery, from 1D-sizing through rotor dynamic analysis to prototype design. Participating in various projects extended our experience to fluid-structure interaction, tool-chain development, and custom design all the way to prototype testing.

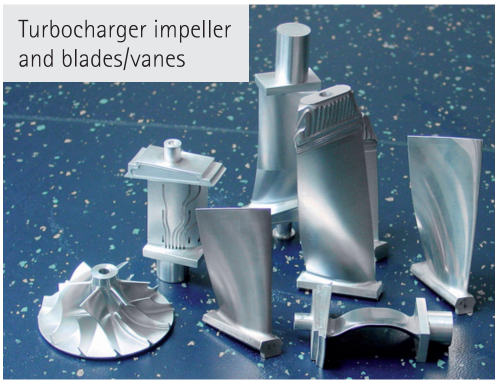
For the aerodynamic design, we use our competency in applying commercial flow solvers ANSYS, Numeca, and STARCCM+, as well as the research flow solver TRACE by the German Aerospace Center (DLR, Deutsches Zentrum für Luft- und Raumfahrt).

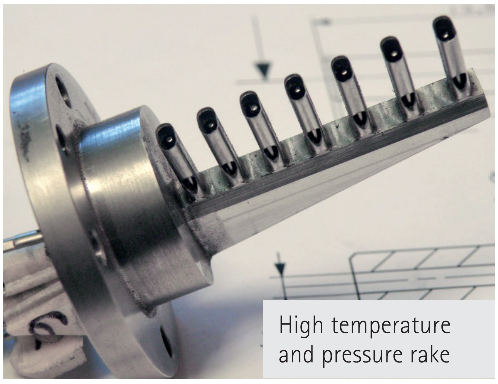
Structural design is performed with the Finite Element Method (FEM)-solver ANSYS Mechanical and rotor dynamics with MADYN.

Our machine shop produces most components in-house for a fast turnaround and changes at short-notice. The production portfolio ranges from simple parts up to challenging 3D blade shapes. A proven network of external suppliers extends our manufacturing volume and capabilities.

Development and design of a wide variety of turbomachinery systems according to customer specifications.

Prototyping at TFD


Turbocharger impeller and blades/vanes


High temperature and pressure rake

Machining

- → Complete CAD/CAM chain
- → CNC 3, 4, and 5-axis milling machines
- → CNC lathe
- → Manufacturing of 3D turbine and compressor blades
- → 3D Polyjet printer for polymer parts
- → 3D additive manufacturing of stainless steel, nickel based alloys, and aluminum

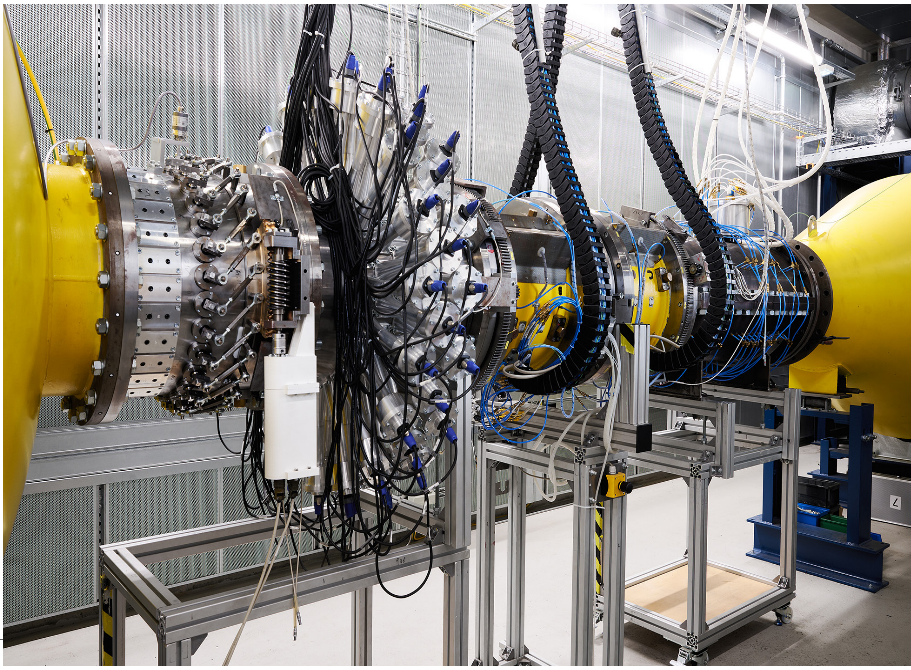
Instrumentation

- → Design, manufacturing, and assembly of test rigs
- → Design and manufacturing of multi-hole, unsteady and steady flow probes
- → Integration of instrumentation in blades (pressure, temperature, strain)
- → Instrumentation of third-party test rigs
- → Conceptual design of electrical circuits for instrumentation and data acquisition

Interdisciplinary Projects

Aeroacoustics: Sound Propagation in Turbomachines

The minimisation of noise from modern aero engines is a research field of high significance to society. It requires knowledge of a propagation of acoustic modes. With a current focus on low-pressure turbines, our Aeroacoustic Wind Tunnel (AWT) provides the required experimental data for the development and validation of models for the prediction of the acoustic transmission in turbomachines. Recent improvements of the AWT aeroacoustics' design enables our measurements of the acoustic fields to be conducted with small uncertainties and a small number of microphones.



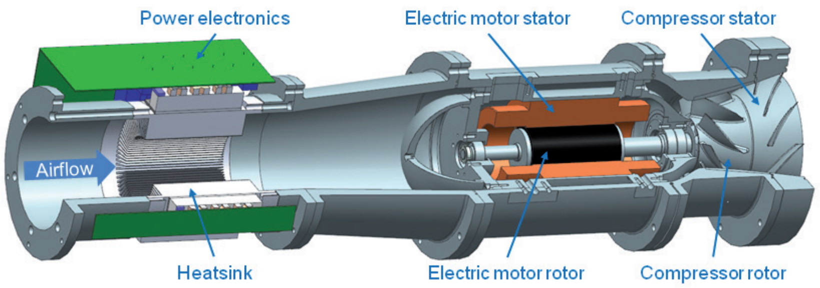
Aeroacoustic Wind Tunnel

Co-Optimisation of Turbomachinery and Electrical Drives: High-Lift System for Future Commercial Aircraft

We cooperate with the Institute for Drive Systems and Power Electronics (IAL) at LUH and with our aeronautical engineering partner at the Technical University Braunschweig (TUBS) in an interdisciplinary design as part of the CRC 880 collaboration. In order to meet the power-to-weight ratio required for modern aircraft the interactions and design trade-offs between the compressor and the electrical components are modelled.

The compressor system is a core component for a novel aircraft high-lift system, which uses a combination of boundary layer suction and active blowing over coanda flaps. Based on the Computer Aided Design Optimization (CADO) tool of the von Karman Institute for Fluid Dynamics (VKI), a tool chain has been developed for interdisciplinary compressor design optimisation of electrically powered compressor systems. CADO uses an evolutionary algorithm to optimise the parameterised compressor's geometry. An evaluation of compressor designs is performed automatically using computational fluid mechanics and computational structural mechanics. Since the electrical components have a big impact on the weight of the whole compressor system, electromagnetic models for those components by the IAL are included as well as to reduce the system mass, and to increase the system efficiency.

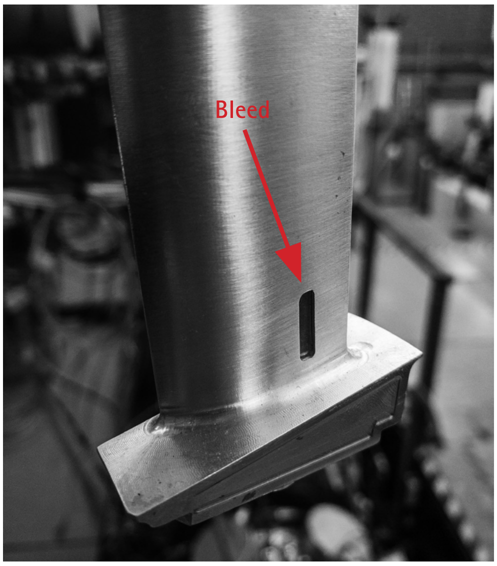
Electrically driven mixed-flow compressor for a high-lift system in future commercial aircraft



Flow Control in Turbomachinery: Adaptive High-Speed Compressors

Increasingly strict regulations regarding aircraft emissions necessitate innovative approaches to the design of aero engines that perform efficiently over a wide operating range. Active flow control is such an approach: it combines advanced technologies such as fluid injection, aspiration, and shape-variable blades, to design a compressor that adapts itself aerodynamically for improved overall performance.

To shape future compressor technology, it is necessary to challenge – and to outperform – current paradigms in the aerodynamic design and manufacturing of turbomachinery components. The combined application of various active flow control methods increases the available design space on the performance map tremendously and allows the targeted manipulation of the three-dimensional flow field. Of course, such a task would not be possible without the use of advanced computational fluid dynamics. Active flow control requires a forward-thinking approach to manufacturing to realise the complex blade geometries with inner ducts, aspiration, and injection slots. To make this possible, we routinely venture into unconventional methods of manufacturing and treating blades. Beyond specialised soldering techniques, laser cladding and the like, rapid prototyping by additive manufacturing is a promising tool for future active flow control applications.



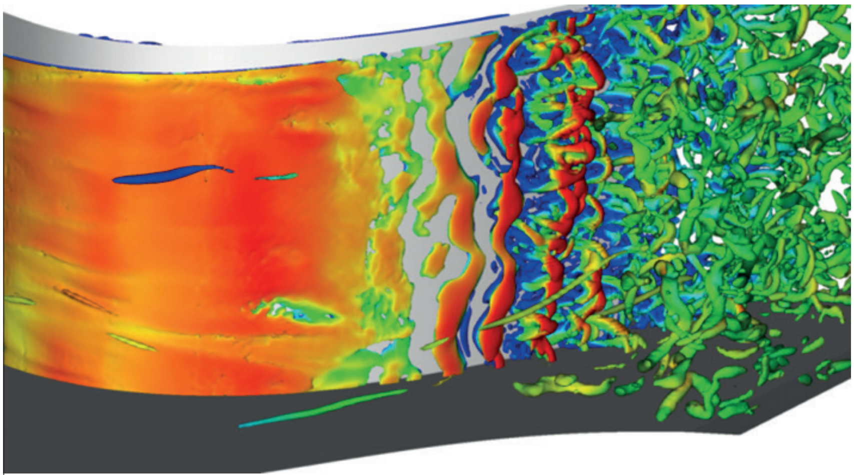
Stator vanes for active flow control with bleeds for aspiration

Computational Fluid Dynamics (CFD)

Industrial use of CFD

Computational Fluid Dynamic (CFD) is a valuable tool for understanding and improving industrial applications. Optimisation of turbomachinery or its components through correct use of CFD lowers costs for the experimental validation of a new design and shortens the time-to-market.

Currently, CFD in industry solves the Reynolds-Averaged Navier-Stokes (RANS) equations with two-equation eddy viscosity models to account for turbulence. However, these models are designed and calibrated for a finite number of test cases considering simplified flow problems only. We are highly experienced in developing specialised extensions of turbulence-models to achieve an accurate prediction of turbomachinery flows. Our computational models of radial and axial turbomachinery cover time-averaged and time-resolved numerical simulations accounting for secondary flow systems and probes in the flow, if required.

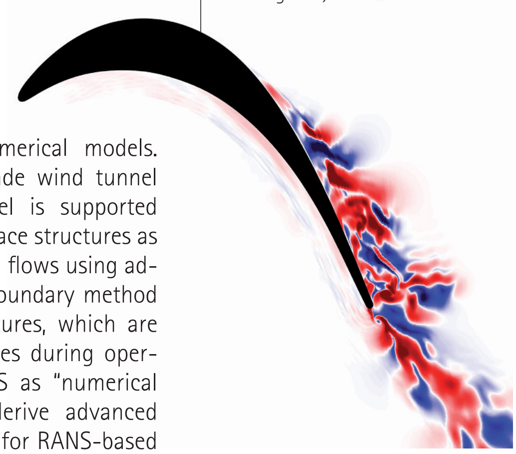


Vortex detection with Lambda-2 criterion of T161 profile by DNS

Bridging the Gap using Hybrid CFD Methods

Complex flows (e.g. separated flows) often require sophisticated simulation approaches beyond the capabilities of RANS models. At the same time, engineering problems often require extensive flow domains where the necessary computational effort precludes the use of scale-resolving simulations. Hybrid CFD methods provide a viable alternative for these cases. We have, therefore, incorporated the partially scale-resolving Scale-Adaptive Simulation (SAS) approach into our CFD toolbox to successfully model inter-component interactions, e.g. turbine-diffusor interactions in the presence of strong secondary flow and massive boundary-layer separations.

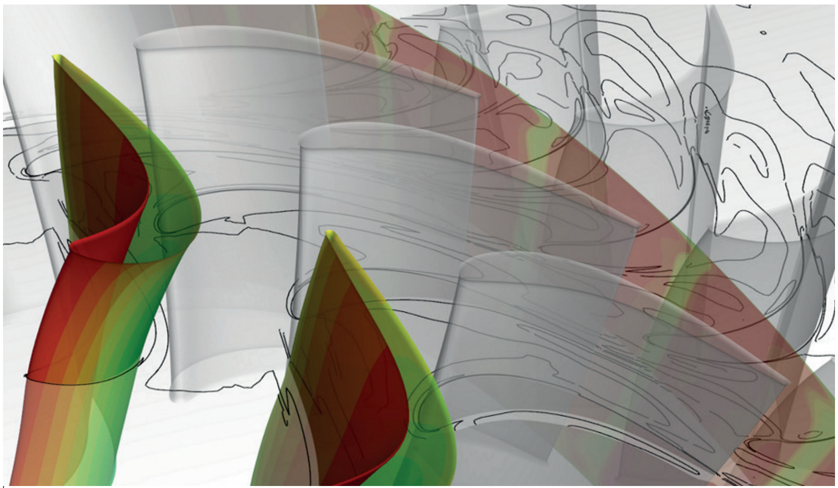
Velocity in spanwise direction of the T106d profile by DNS (red=positive, blue=negative)



High-Fidelity CFD

High-Fidelity CFD solves the Navier-Stokes equations by resolving turbulence in the flow completely (Direct Numerical Simulation, DNS) or to a reasonable level (Large Eddy Simulation, LES). Therefore, DNS and LES are excellent tools for the analysis of complex flows.

For example, we use DNS and LES to investigate the profile aerodynamics of low-pressure turbine blades for aero engine aeroelasticity involving oscillating blades. We analyse the flow through labyrinth seals by means of LES and use the results to improve numerical models. Roughness research in our cascade wind tunnel and boundary-layer water tunnel is supported by DNS. We simulate complex surface structures as well as riblets in turbulent channel flows using advanced tools like the immersed-boundary method to model complex surface structures, which are found in compressors and turbines during operation. We also use DNS and LES as "numerical experiments" from which we derive advanced turbulence and transition models for RANS-based industrial CFD.



Analysis of rotor-stator interactions by unsteady flow simulations

Turbine Optimisation

Modern day turbine designs, which are conventionally optimised by utilising steady-state single-passage approaches, already yield efficiencies of more than 90%. Further improvement requires consideration of unsteady effects, particularly the rotor-stator interaction. The interactions affect not only the work extraction losses, but they also affect components' size and weight.

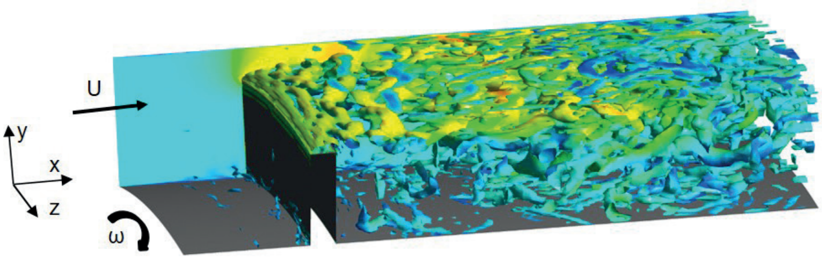
To explore turbine designs optimised for unsteady work extraction, a 1.5-stage low-pressure turbine configuration has been designed, manufactured, and operated for an industrial partner. The experiments are supported by pre-test and post-test numerical analysis. The variation of the axial-gap size and stator clocking has helped us to identify the optimal axial spacing and gain a deeper understanding of the underlying physical phenomena, e.g., wake-blade interaction, potential-field interaction, and secondary-flow interaction.

For the present turbine in particular, a considerable discrepancy between steady state simulation and the flow field observed downstream of the second stator blade row was identified. This discrepancy is due to the missing interaction of upstream wakes with the downstream blading in steady-state mixing-plane simulations. The use of time-accurate methods considerably increases the predictive performance of the numerical simulation.

Labyrinth Seal Flows

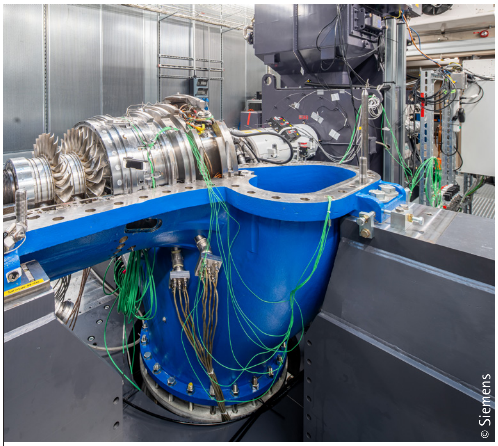
Contact free labyrinth seals are commonly used in turbomachines to minimise leakage of the working fluid between the rotating blade shroud and casing. However, a small leakage flow cannot be prevented entirely, resulting in disturbances of the main flow upon re-entry of the leakage into the main flow path. This is to the detriment of the overall efficiency due to lossy interactions between the leakage and secondary flow. Variations in shroud-cavity geometry on the local flow field are used for an improved understanding and a more efficient design of the shroud cavity.

The prediction of the experiments' labyrinth seal flows with RANS-based simulations is not sufficiently accurate. This wrong prediction of labyrinth seals can lead to wrong design choices and, more dangerously, aeroelastic instabilities. The insight into the highly turbulent flow in labyrinth seals provided by experiments, even with PIV, is not sufficient to identify the source of the modelling deficit of RANS turbulence models and to develop improved models for industry. Large Eddy Simulation (LES), by contrast, provides a deeper understanding of the flow as it resolves most of the energy containing turbulent scales, while the modelling errors are limited to the dissipative scales. These highly accurate LES results help us to develop improved RANS turbulence models for industrial labyrinth seal design.



LES of the turbulent flow in a generic labyrinth seal

High-Fidelity and Multi-Stage Testing



Multi-stage air turbine in preparation
for aerodynamic experiments

Pre-Test Prediction for Instrumentation Design

In preparation for experimental measurements on turbomachinery test rigs, pre-test numerical simulations of the test rig serve to define the most suitable location for sensor placement, estimate the expected range of measurement results, and thereby the experimental parameters, and ensure the production of meaningful data in later project stages. Based on the results, the sensitivity of target phenomena is analysed with respect to measurable parameters and the required measurement accuracy is defined. The results aid in the selection of appropriate measurement techniques, sensor ranges, and operating conditions for the sensors and probes.

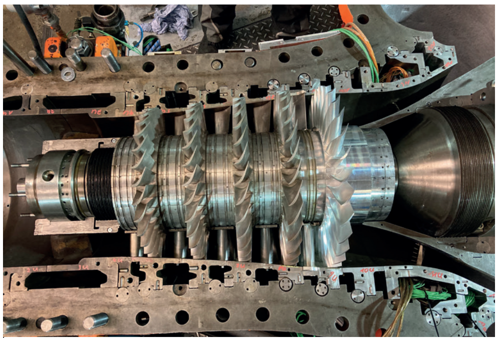
High-Fidelity Testing

High-fidelity experimental testing is required for the validation of complementary numerical simulations. Often, the correct simulation of innovative turbomachinery systems cannot be assumed without confirmation by measured data. In order to derive meaningful data from turbomachinery rig tests, challenging criteria must be met. Among those criteria are highly precise, accurate, and stable operating conditions, fine temporal and spatial resolution of the phenomena under investigation, and low measurement uncertainty.

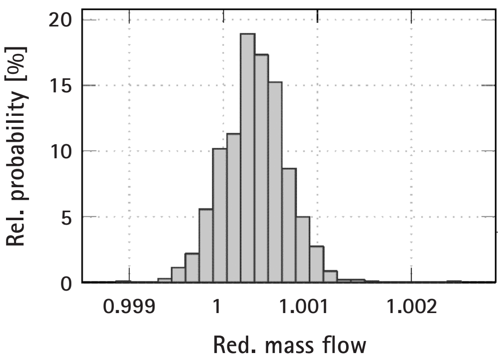
We provide stable operating conditions by an accurate automatic control of the pressure ratio, mass flow rate, and rotational speed. The operating conditions allow maintaining constant non-dimensional operating conditions, e.g. the Mach number similarity.

Using the pre-test prediction as a guide, the required temporal and spatial resolution for targeted phenomena are defined. Targeted measurement technology, such as time-resolved pressure probes, hotwire probes, miniaturised flow probes, or optical measurement methods is implemented to record experimental data.

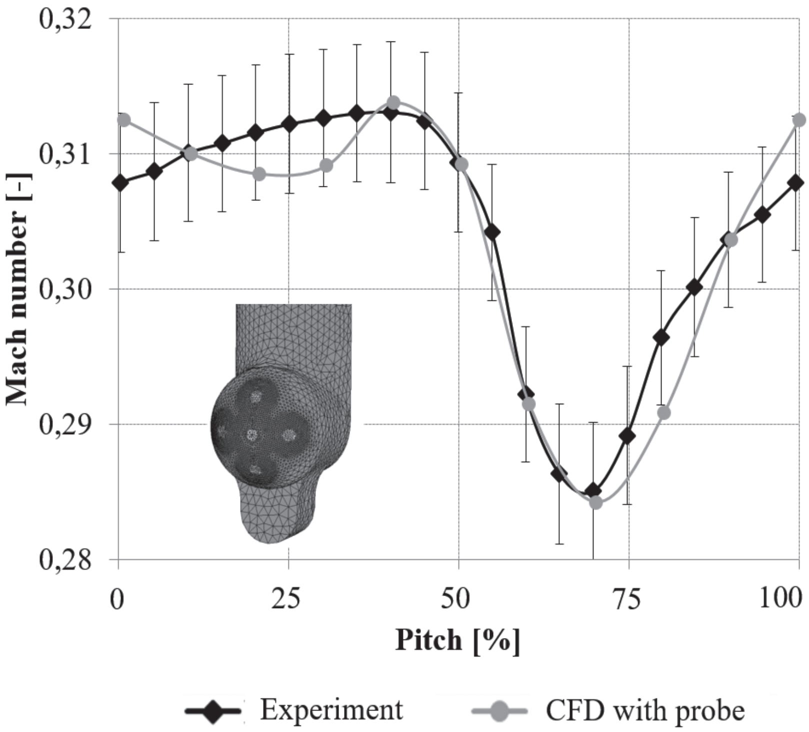
As the causal relations of unsteady flow phenomena in turbomachinery often span across multiple stages, our rotating test rigs for axial turbines and compressors offer the possibility for test configurations of up to seven stages. This allows generating engine-representative conditions in the test rigs.



Five-stage gas turbine design for experiments
in aeroelasticity



Histogram during testing at one operating point



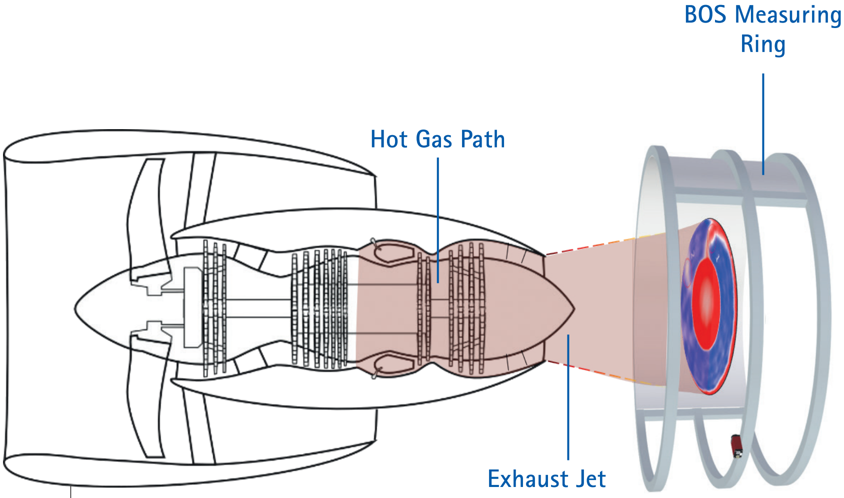
Post-Test CFD including the probe vs. experiment in a five-stage turbine
(errorbars = 95% confidence interval)

Post-Test Prediction

The primary goal of a post-test prediction is the verification and validation of the physical assumptions made in the initial project phases, particularly during the pre-test analysis. In its most simple form, this means a comparison of analytical theory and the experiments conducted. In more complex test cases, particularly for complex rotating turbomachinery rigs, numerical simulations are the primary focus.

Comparing both, integral stage or system parameters and local flow quantities, the plausibility of the experimental data is verified and numerical models are validated. This often requires a CFD analysis of the instrumented test rig, i.e. including flow probes and other intrusive instrumentation.

If the pre-test assumptions or the experimental results do not line up with the post-test results, they must be challenged and reworked. Hence, post-test prediction increases the testing quality and is an important part of our scientific Quality Assurance System within the research, and an integral part of each project with our industrial partners. Once a valid framework has been derived, the numerical post-test prediction can be used to extrapolate results outside the range of the experimental measurements and for a close look at highly resolved flow features in both, space and time.



Schematic of the density measurement in the exhaust jet of a jet engine
(red = low density, blue = high density)

Exhaust-Jet Analysis

Beyond the testing of multi-stage compressor and turbine models, we developed and continuously improve a method for an automated troubleshooting of aircraft engines. The Background-Oriented Schlieren (BOS) method (cf. „Instrumentation & Development of Measurement Techniques“) allows physically measuring the density distribution in and around the exhaust jet. A tomographic analysis of the multi-view images is used to identify defects in the hot gas path (HGP). An algorithm based on Support Vector Machines (SVM) detects and classifies a multitude of defects in the HGP, such as, wreck of cooling, blade ruptures, and combustor malfunctions.

New Test Facilities

The specifications of the compressor station are summarised below. Thanks to the modern compressor station, the research with our test rigs can rise to a new level. Share this exciting challenge with us and benefit from our excellent test facilities. Of course, we can ensure the operation within the specifications of our test rigs described on the next pages.

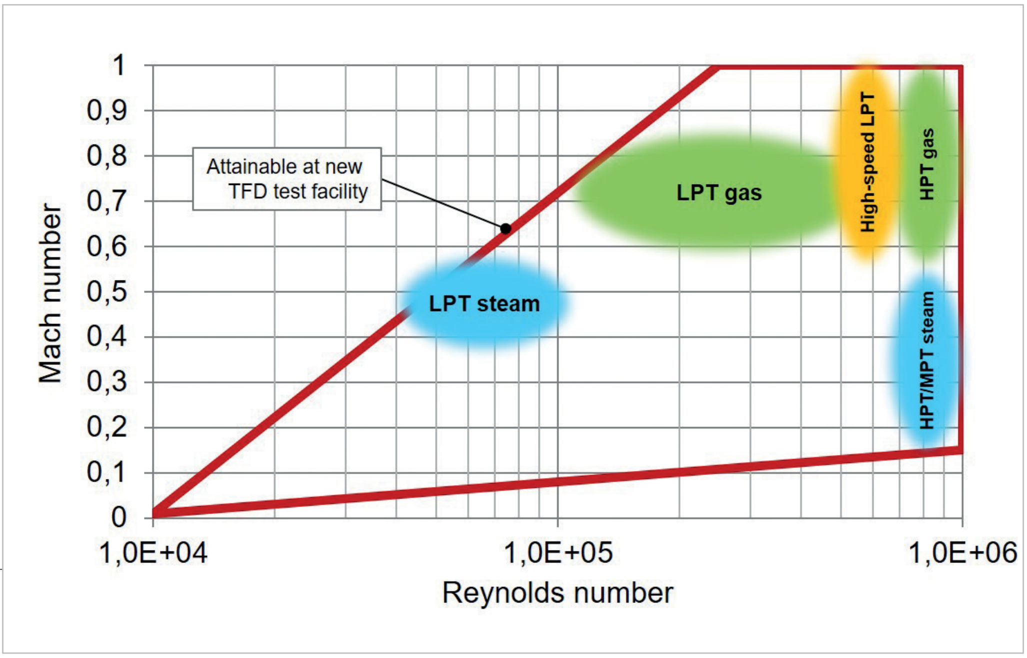
Key facts

➞ Dimensions 27 m x 15 m x 9 m
➞ Power 6 MW
➞ Mass flow rate up to 25 kg/s
➞ Pressure ratio up to 6
➞ Inlet pressure 0.3 … 8 bar
➞ Inlet temperature 35° C … 200° C

Our state-of-the-art compressor station can either operate in open loop or closed loop configuration. This provides opportunities for experiments emulating chassis and altitude, and for decoupling the variation of Mach number from the variation of Reynolds number. The compressor station consists of two roots blowers and two screw compressors, delivered by Aerzener Maschinenfabrik GmbH. They can be operated serially or in parallel.

Experimental investigations under challenging conditions and a wide-load range are possible. In particular, dynamic-transient partload experiments, which represent the future requirements of gas and steam power stations, are feasible under high standards of precision and reliability. The compressor station allows a four-fold overall pressure rise. In open-circuit operation, inlet pressures of 6 bar and maximum mass flows of 22 kg/s can be achieved, and in closed loop operation, inlet pressures of 0.3 to 8 bar and a maximum mass flow of 25 kg/s are possible.

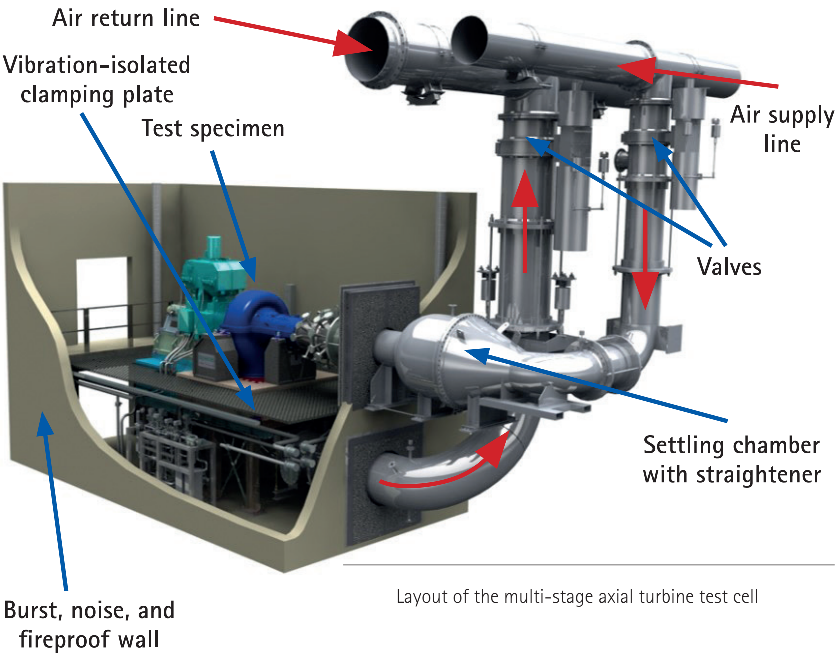
To achieve low Reynolds numbers at high Mach numbers, the system is designed for a minimum pressure level of 0.3 bar and a maximum pressure level of 8 bar. An additional compressor has been installed to achieve this range in pressure levels. A highly advanced cooling system is integrated into the controls of the pressure system to independently set Mach number and Reynolds number as shown below. The transient dynamics of aircraft engines and the future operation of gas and steam turbines can be dynamically emulated in rotating turbomachinery.



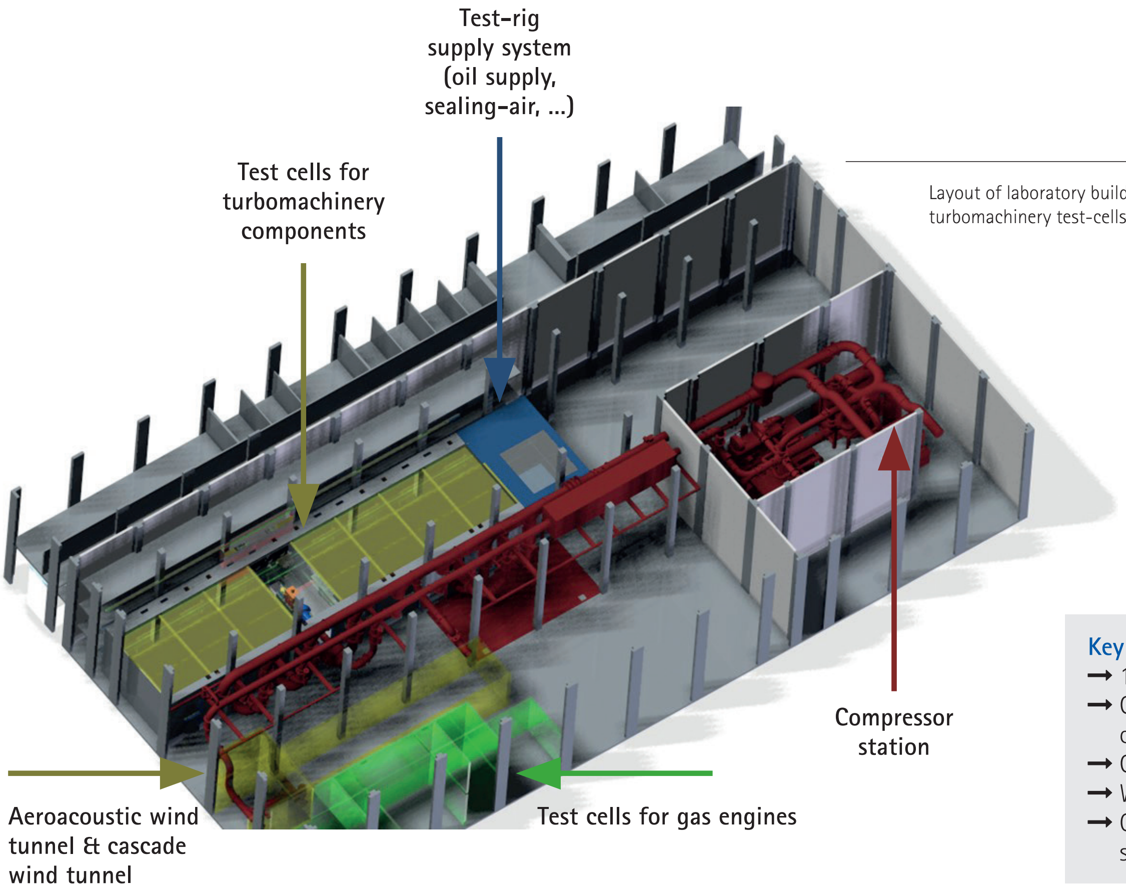
Attainable Mach number and Reynolds number area with the new compressor station

Turbine Test Cell

Each of the 14 modular test cells is burst and fireproof, and insulated acoustically, thermally, and vibrationally by steel reinforced concrete foundations and walls. As an example, a three-dimensional model of the overall layout of the axial turbine test cell is shown (right). Each clamping plate can take all structural and aerodynamic loads of the rig and the adjacent inlet and outlet piping. Thus, the test rig is free of external vibration and external forces. In order to meet structural, health and safety, and secondary supply system requirements, the building consists of a strong foundation with an overall housing structure and modular test cells. The test articles (turbine or compressor) are lifted into the test cell by crane from above after removing the concrete cover.



Layout of the multi-stage axial turbine test cell



Layout of laboratory building with multiple turbomachinery test-cells

Key facts
- 14 separate test cells
- Cutting-edge compressor station
- Control rooms
- Workshops
- Offices for research staff

Test Rigs

High-Speed Axial Compressor

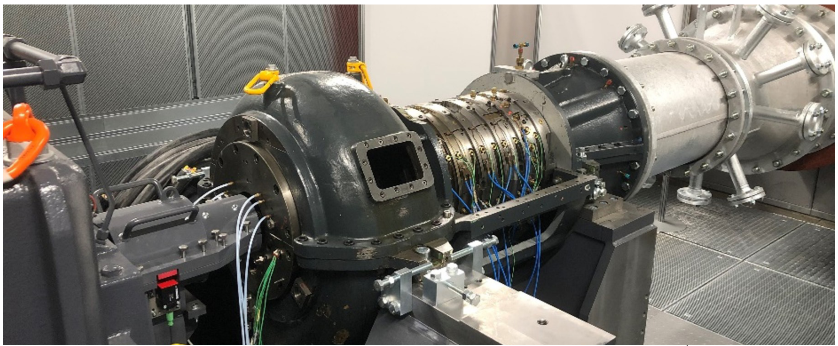
Key facts

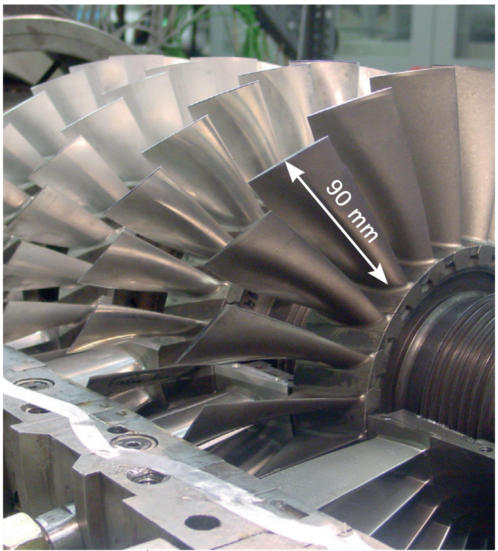
- Rotational speeds up to 30,000 rpm
- Power up to 2 MW
- Configurations: currently 1½, 4½ stages

The axial-compressor test rig is used for a wide range of aerodynamic and aeroelastic investigations in the subsonic and transonic flow regime. The test rig can be equipped with a secondary-air supply to investigate active flow control. Various multi-stage and single-stage configurations are used for advanced aerodynamic blading designs (CDA, Bow, Sweep). A ring throttle immediately downstream of the diffusor enables this test-rig to be used for stall investigations without going into surge.

Active flow control by blowing and aspiration was shown to be effective on a rotating compressor for the first time. A significant multi-stage impact of aspiration was demonstrated on the four-stage configuration. A single-stage blade integrated disk (Blisk) configuration was used to quantify aerodynamic damping in an aeroelastic investigation. For this purpose, the conventional instrumentation was extended by a contactless tip-timing measurement system to determine blade vibrations and an acoustic excitation system to induce blade vibrations.

Higher mass flows, rotational speeds, and pressure ratios than those listed in the key facts can be attained in our new test facility to accommodate new compressor designs, which we create and implement together with our customers and research partners.





Four-stage high speed axial compressor

High-Speed Axial Turbines

Key facts

- Rotational speeds up to 20,000 rpm
- Power up to 3 MW
- Configurations: currently ½, 1, 1½, 2, 4, 5, 7 stages unshrouded and shrouded

The high-speed air turbine test rig is highly adaptable to various turbine configurations, making it suitable for the investigation of multi-stage phenomena, unsteady aerodynamics, aeroelasticity, and aeroacoustics. Measurement capabilities include high accuracy pressure and temperature instrumentation as well as turbulence, unsteady pressure, tip-timing, and aeroacoustic measurements. Acoustic excitation of blade vibrations and PIV (Particle Image Velocimetry) are used for the in-depth investigations of nodal turbine designs, and fundamental aerodynamic and aeroelastic phenomena.

Mass flows, rotational speeds, and pressure ratios higher than those listed in the key facts can be attained in our new test facility to accommodate new turbine designs, which we create and implement together with our customers and research partners.

Four-stage high speed axial turbine

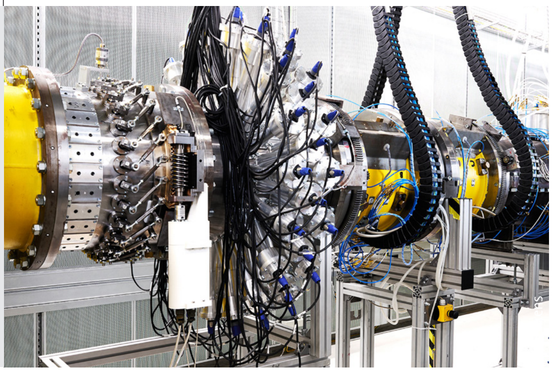
Aeroacoustic Wind Tunnel

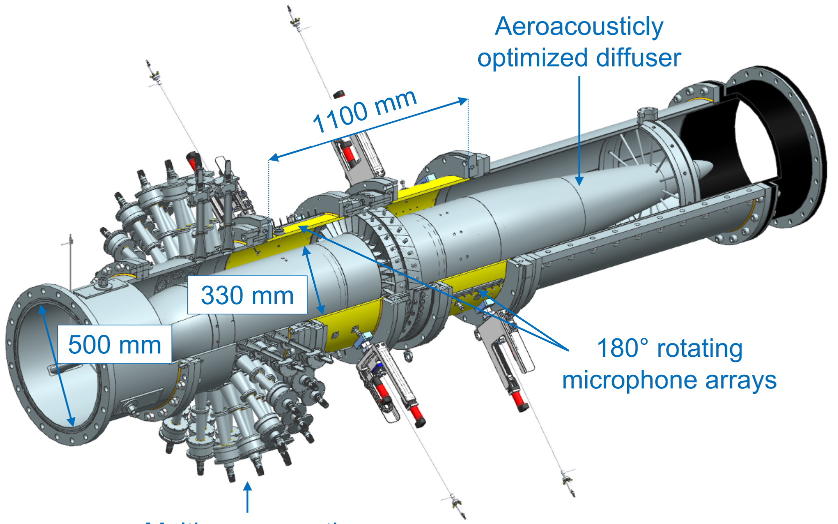
The Aeroacoustic Wind Tunnel (AWT) is a test rig for the investigation of aeroacoustic phenomena in ducts and turbomachines. It comprises a silencer, which also functions as a settling chamber, the measuring section and an anechoic termination. The modular measurement sections are designed in order to provide optimal acoustic boundary conditions such as minimal acoustic reflections and a low inherent noise level at the inflow.

Aerodynamic probes and sound pressure transducers (e.g. microphones, dynamic pressure probes ("Kulites®"), and pressure sensitive paint) are used to measure the acoustic field. In the AWT's current design, a modal sound generator, consisting of an array of 3 x 20 loudspeakers, is used to superimpose a defined synthetic acoustic field onto the mean flow. The sound propagation of the acoustic field through blade rows is measured using 360°-rotating arrays of microphones mounted flush with the wall. A Radial Mode Analysis (RMA) is used to decompose the single microphone measurements into acoustic modes propagating in the duct.

AWT with single-row acoustic excitation unit

Key facts
- → Mass flow rate up to 25 kg/s
- → Pressure ratio up to 6
- → Inlet pressure 0.3 ... 6 bar
- → Sound pressure level at modal sound generator up to 160 dB
- → Frequency range 500 Hz ... 6 kHz





AWT with multi-row acoustic excitation unit

Linear Cascade Wind Tunnel

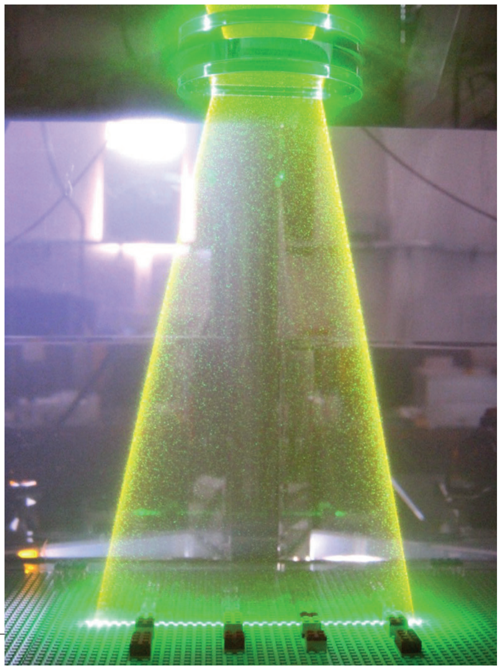
The Cascade Wind Tunnel is used for the investigation of compressor and turbine blades. It is an Eiffel-type wind tunnel with a settling chamber and turbulence grids in front of the test section. The Wind Tunnel is equipped with a suction system ensuring a 2D passage flow by suppressing the side-wall boundary layers and reducing the secondary flow. The test blade is separated at mid-span into a reference half-blade and a test half-blade. The wake of each half-blade is measured with parallel total pressure probes such that the differences in total pressure are determined directly by differential pressure measurements. This makes the comparison of losses between the reference half-blade and test half-blade robust against a variation of the operating conditions of the wind tunnel.

Due to the easy access, a large variety of measuring techniques, e.g. 3D Particle Image Velocimetry (PIV), Constant Temperature Anemometry (CTA), density field measurements (BOS), and conventional pressure and temperature probes can be used to allow the investigation of compressor and turbine blades aerodynamics at different spatial and temporal scales. Using our experience with Laser-2-Focus (L2F) anemometry to measure the particle density in the air and the possibility of housing the test section, we can perform fouling and erosion tests with dust from a dedicated particle generator providing a well-defined size distribution.

Key facts
- → Mass flow rate up to 22 kg/s
- → Adjustable turbulence intensity
- → Minimum number of blades 5

Linear cascade wind tunnel

Key facts
- ➞ Mass flow rate up to 250 kg/s
- ➞ Velocity 0.1 ... 1 m/s
- ➞ Axial flow pump power up to 30 kW
- ➞ Size of measurement section 0.5 m (width) x 2.5 m (length)



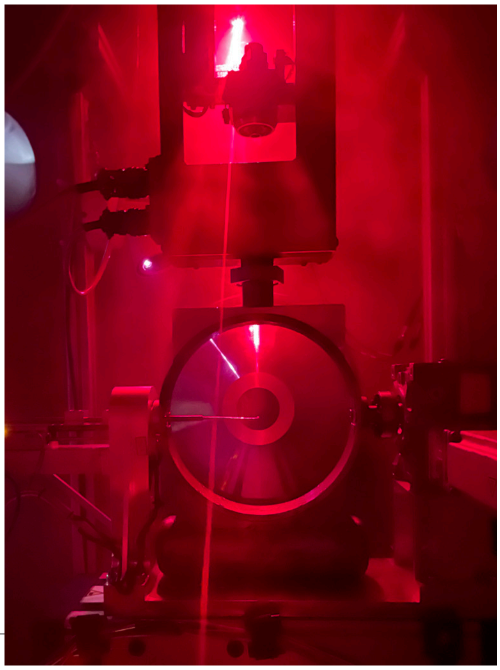
PIV light sheet in the water tunnel

Boundary-Layer Water Tunnel

The water tunnel is suitable for studying fundamental fluid mechanic processes by scaling up length scales and reducing time scales, due to the low kinematic viscosity of water compared with air. The free access through glass walls facilitates optical methods such as PIV. A pressure gradient can be imposed to generate engine-like acceleration or deceleration of the boundary layer.

Experience with refractive index matching in particle image velocimetry (RIM-PIV) allows near-wall measurements even between the roughness elements of scaled up rough surfaces and reduces measurement errors, which would be induced by refractive index mismatch at optical interfaces. Together with the Institute for Multiphase Processes (IMP) we developed a new method using hydrogels for improving boundary-layer measurements with PIV close to the wall and measuring flows even behind objects in the flow.

Key facts
- ➞ Pressure up to 6 bar
- ➞ Temperature 20 ... 180 °C
- ➞ Re number 350,000 ... 700,000
- ➞ Ma number 0.1 ... 1.0

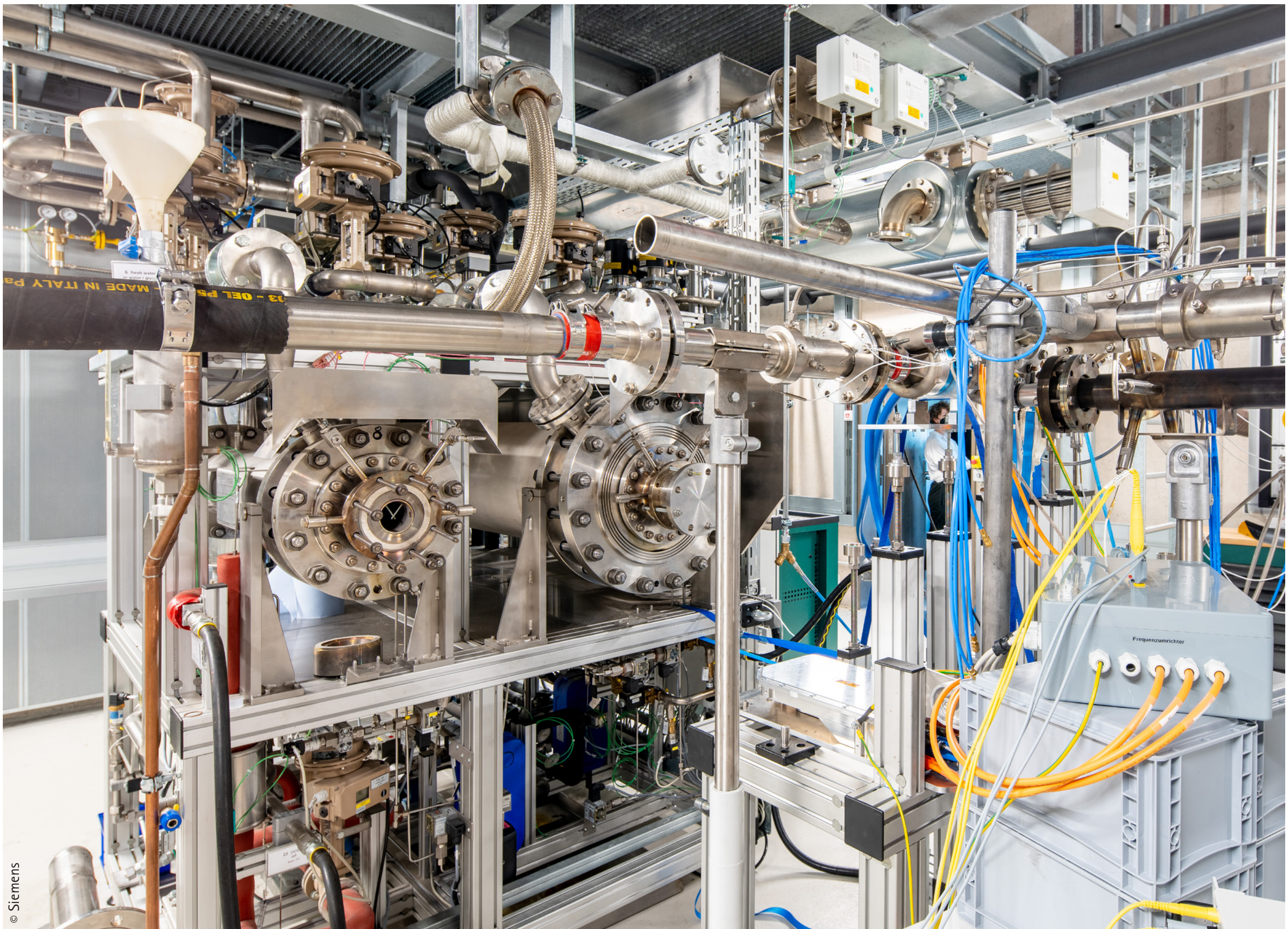


Aerodynamic probe in the calibration channel

High-Speed Calibration Wind Tunnel

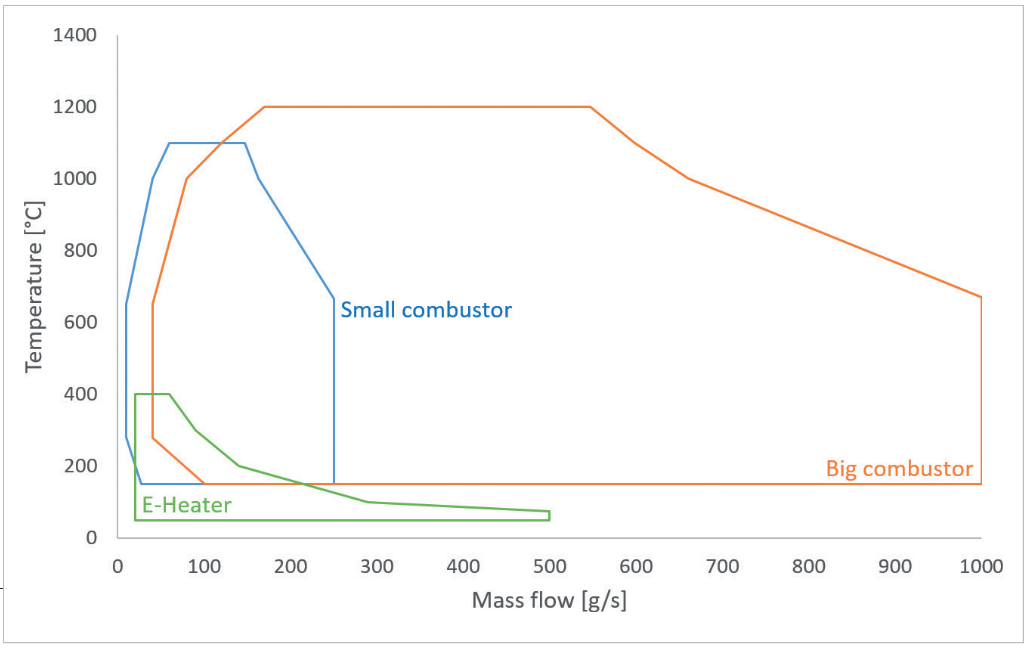
Accurate measurement technology is required to accurately measure the flow in the institutes' test benches. For this purpose, the TFD has a calibration wind tunnel that can calibrate all types of aerodynamic probes over a wide range of boundary conditions. The calibration wind tunnel can be operated at variable temperature, pressure and Mach number.

Test Rig for Turbocharging Systems and Electric Air Compressors



For research on exhaust gas turbochargers, turbocharging systems for fuel cells, and electrically driven compressor systems, we operate a test rig for turbocharging systems and electric air compressors. Our projects include the development of new turbocharging and compressor systems and the optimisation for existing applications. For the successful research projects, the test bench combines state-of-the-art and highly accurate instrumentations and controls with a high adaptability to a wide range of applications and the implementation of advanced measurement techniques. We achieve versatility by a modular structure of the test rig and a well matched infrastructure.

Test cell of the test rig for turbocharging systems and electric air compressors



Operating ranges of the turbocharger test-facility for three heat sources

The test rig features the following components:

- three hot gas generators, which can be combined with a thermal power up to 800 kW (operating map above),
- a compressor backpressure unit for setting the boost pressure,
- a lubricating oil conditioning unit to control the pressure and temperature in the bearings (max. 150°C at 6 bar),
- two independently controllable cooling water conditioning units to maintain a uniform inlet temperature for water-cooled turbochargers,
- a compressor closed-loop unit to vary the turbine operating range independently of the compressor,
- a compressor intake air conditioning unit to adjust the intake air with up to 100% relative humidity at up to 50°C,
- a DC voltage source for electric drives up to 750 V DC,
- various inverters for synchronous and asynchronous motors.

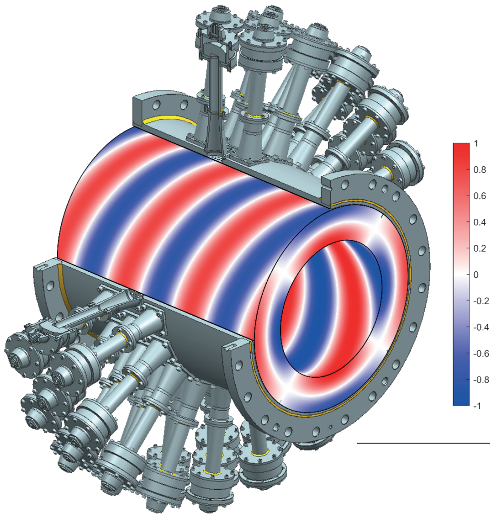
The high reproducibility of the operating conditions is a perfect basis for performing reliable and reproducible measurements and, thus, for obtaining substantiated and reliable data.

Axial turbine turbocharger developed in-house for turbocharging lean-burn engines

Instrumentation & Development of Measurement Techniques

Acoustic Mode Generation

We operate acoustic mode generators, which consist of loudspeaker arrays, whose driving signals are matched such that the resulting in-duct sound field provides a tonal modal excitation. For aeroelasticity, we use single-row loudspeaker arrays to excite specific vibrations in rotating blade rows of our high-speed axial test rigs and measure their response. In aeroacoustics, we employ single-row and multi-row acoustic mode generators to excite defined synthetic sound fields, and to measure the propagation through turbomachinery stages with a high signal-to-noise ratio.



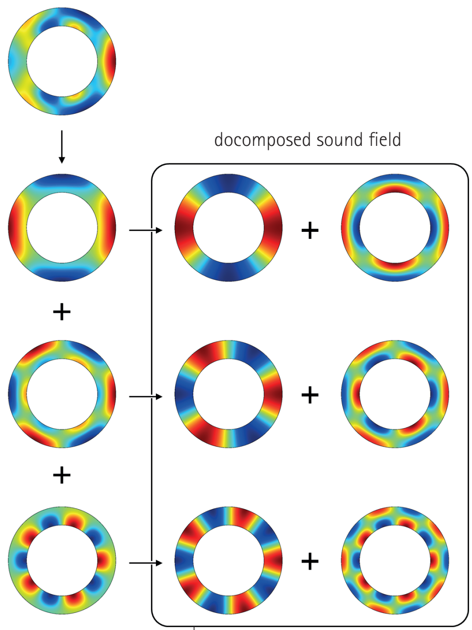
Schematic of three-row AWT's acoustic sound generators

Acoustic Mode Analysis

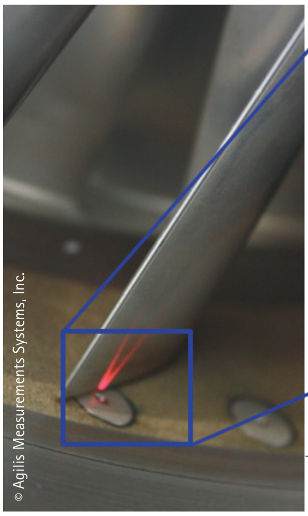
The Aeroacoustic Wind Tunnel (AWT) is equipped with rotating segments in which microphones are installed flush with a duct wall. Using analytical models of the aeroacoustic field, the locations of the microphones are optimised depending on the required flow conditions and frequency range. This enables us to measure the acoustic fields with the smallest possible measuring error using a minimal number of microphones. The three-row AWT sound generators are able to excite specific modes in a frequency range between 500 and 6,000 Hz. At higher frequencies, secondary modes are also excited and can be separated from the target excitation mode with the help of our mode decomposition tools.

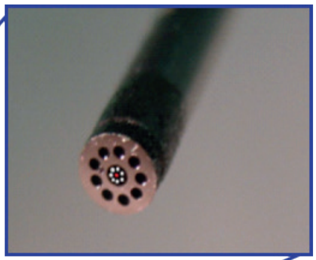
The in-duct mode decomposition tools perform a radial mode analysis (RMA), which decomposes the acoustic field into acoustic modes propagating up- and downstream. The tools are used, for instance, to measure the noise generated in turbomachines or to measure the sound transported through blade rows.

Microphone arrays placed in the shroud of the AWT



Schematic of radial mode analysis



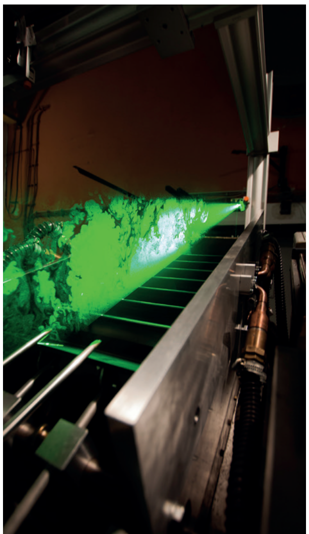


Tip-Timing sensor

Tip-Timing

Blade vibrations can cause High Cycle Fatigue. We use an optical Tip-Timing System to analyse the blade vibrations in detail and to improve future turbomachinery designs.

Within the casing, circumferentially placed sensors transmit a laser beam, which is reflected each time that a blade tip passes. This reflected light triggers a detector measuring the passing time of the blade between sensor positions. In case of blade vibration, the passing times differ depending upon vibrational states and allow us to determine the displacement of the blade.

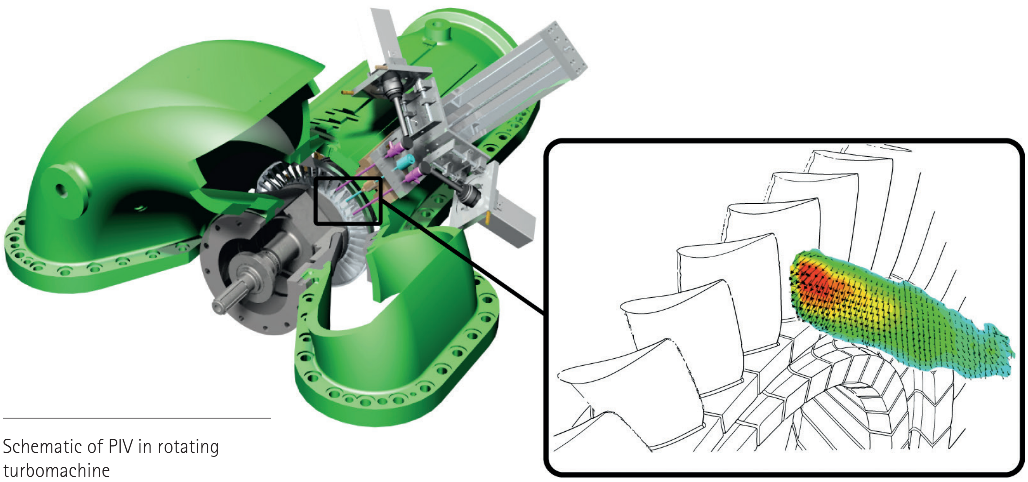


Linear Cascade Wind Tunnel with PIV light sheet

Particle Image Velocimetry

In our research, we widely use Particle Image Velocimetry (PIV). PIV is an optical method to measure 2D and 3D velocity fields, while avoiding interactions of the sensors with the flow. Tracer particles in the flow are illuminated by laser light sheets and photographed twice with a very short delay between the images. The resulting images are cross-correlated to calculate the motion of the tracer particles and, thus, the flow itself. To obtain three-component velocity fields and turbulent quantities, we use the advanced stereo PIV method.

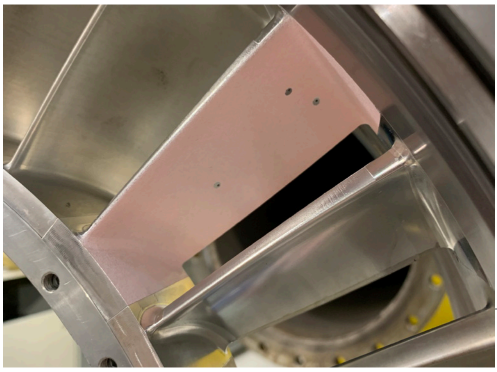
We also use PIV to evaluate the Reynolds stresses and to detect vortices with proper orthogonal decomposition (POD). We mastered the challenges of using PIV in rotating turbomachinery, which are difficult optical access to the flow path, deposition of tracer particles on the optical components, and difficulties in directing tracer particles into the measurement area. For this, we were able to use PIV for measuring the mixing in turbines of shroud leakage and main flow by a detailed pre-test investigation of particle deposition and self-cleaning properties of the flow.



Schematic of PIV in rotating turbomachine

Pressure-Sensitive Paint

Pressure-sensitive paint (PSP) offers further potential for identifying the unsteady, continuous pressure field on turbomachinery surfaces, as investigated in the AWT. PSP is excited with UV light and then emits light at intensities that depend on the ambient pressure. The corresponding 2D responses are then measured by a camera, allowing the measurement of 2D steady and transient pressure distributions, which provides new opportunities for further data analysis.

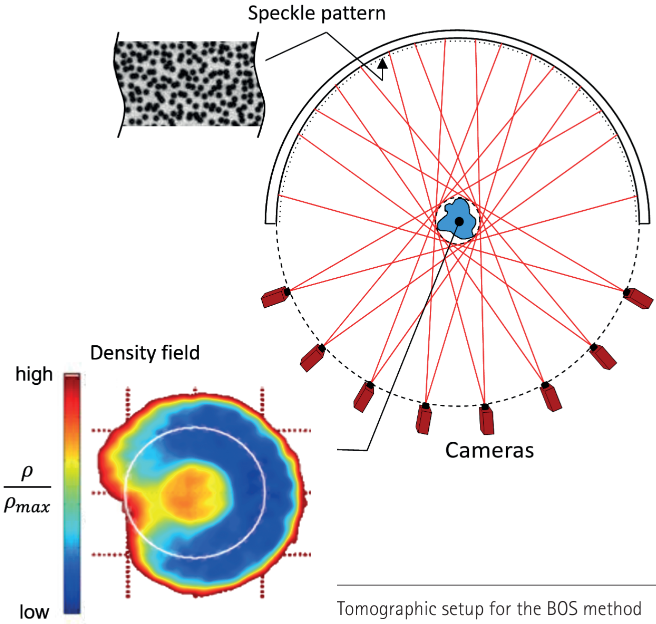


PSP-coated vane for measurements at the AWT

Tomographic Background-Oriented Schlieren Method

The Background-Oriented Schlieren (BOS) method measures the refractive index distribution in a fluid. This can be related to the density field. Using multiple cameras, a random speckle pattern in the background of the fluid allows the detection of changes in the refractive index from the deflection of the rays.

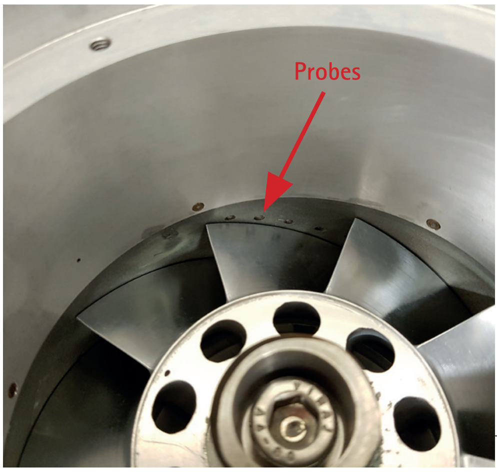
Tomographic algorithms are then used to reconstruct the density distribution. For example, we measured the density distribution in the exhaust jet of an aircraft engine with the BOS method. This allows us to detect density irregularities caused by defective components in the hot-gas path (i.e. the combustion chamber, the high-pressure and the low-pressure turbine) while the engine is installed.



Tomographic setup for the BOS method

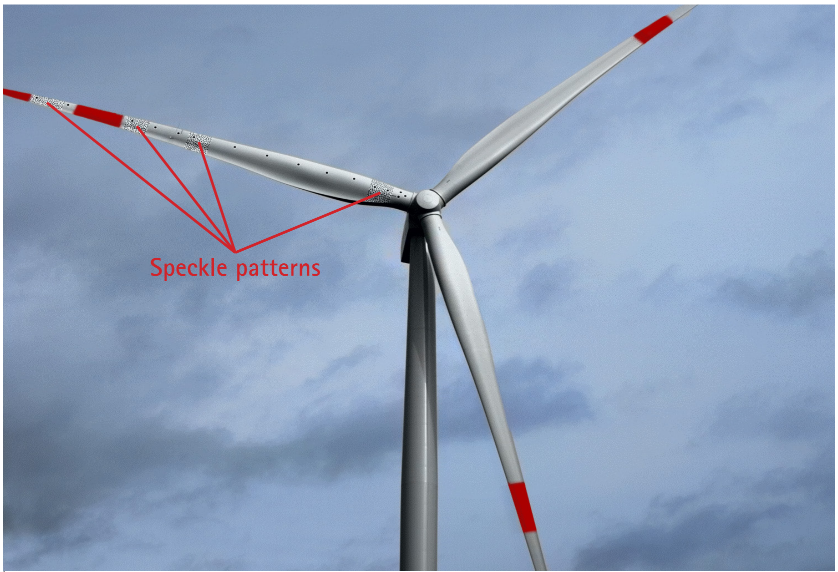
Fast Response Pressure and Temperature Sensors

To be able to investigate highly transient processes, fast responding probes and high-frequency data acquisition are necessary. We use a wide range of different techniques for this purpose. For transient pressure measurements, flush mounted pressure sensors based on semiconductors are used at temperatures up to 1,100°C. Thermocouples with very small diameters, and thus low thermal inertia, are employed for high frequency temperature measurements. The data is recorded by state-of-the-art data acquisition systems with a resolution of 16 bit and a data rate of up to 2,000 kHz.



Probes in a rotor casing

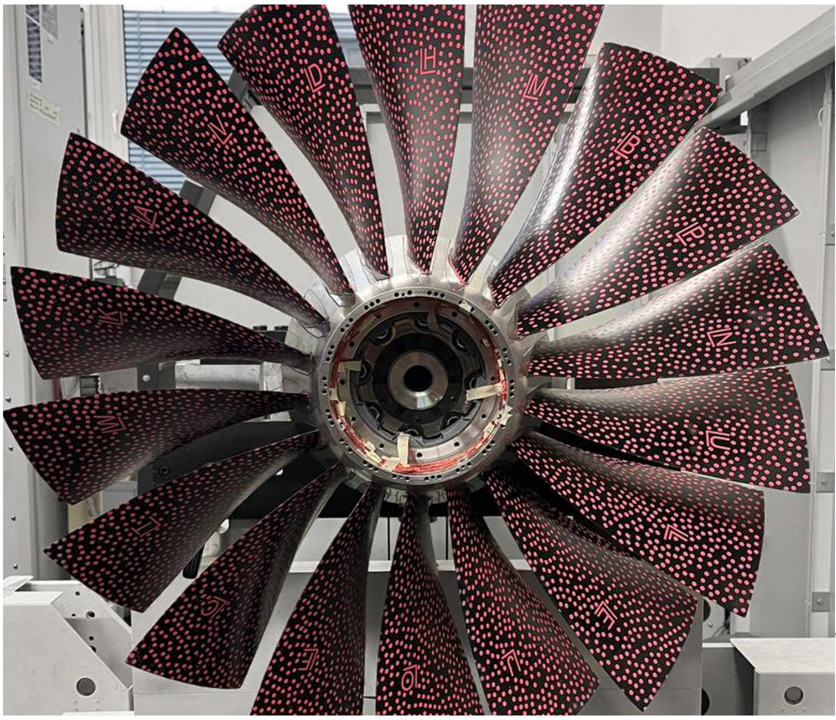
Measuring Blade Deflection in Wind Turbines and Turbomachines



Speckle patterns for DIC on three wind turbine rotor blades

Digital Image Correlation on Wind Turbines

We developed an optical Digital Image Correlation (DIC) technique to measure and monitor the deformation of wind turbine rotor blades. We first verified DIC on a scaled wind turbine test stand and then enhanced the technique to the measurements of multi-megawatt wind turbines. DIC combines methods from photogrammetry, computer vision, image processing, and sub pixel interpolation. Two cameras and a random speckle pattern applied to the surface are required for 3D measurements. Corresponding points detected via image correlation and calibrated cameras allow the triangulation and, thus, the calculation of position and deformation of several hundred measurement points on the blade surface simultaneously.



Digital Image Correlation for Aeroelasticity of Fan Blades

The application of DIC in fast rotating turbomachines, e.g. fans of aircraft engines, further challenges this measurement technique. We implemented a new high-speed DIC setup with two high-speed cameras and a high-speed laser. Due to the short laser pulse duration of less than 210 ns, the motion blur is eliminated even at these high blade tip speeds up to 380 m/s. The system can currently measure spatial deformation and vibration with a sampling frequency of 2000 Hz.

High-speed DIC on rotating fan blades

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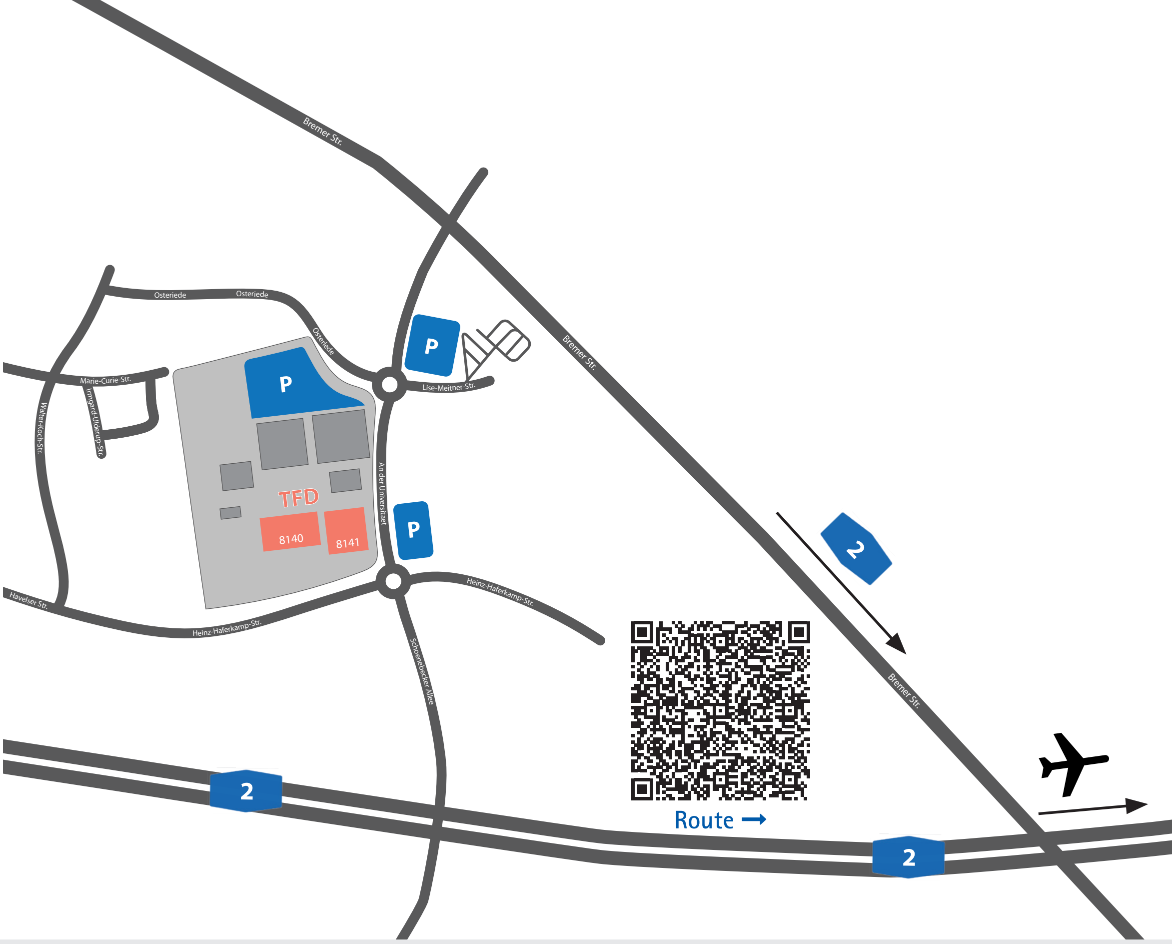
Fan blade assembly of the GP7000 engine.

Contact us



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