Experimental investigation of a turbine sealing cavity exposed to free stream pressure fluctuation

T. Schliwka, L. Malzacher, S. Chemnitz and D. Peitsch

Institute for Aeronautics and Astronautics, Technical University of Berlin, Marchstrasse 12, 10587 Berlin, Germany
tobias.schliwka@ilr.tu-berlin.de, dieter.peitsch@tu-berlin.de
http://www.la.tu-berlin.de

Abstract.
The current investigation examines the impact of a new pulsed unsteady combustion to the turbine sealing cavity, which prevents hot gas ingestion into the inner machine. Sealing flow is ensured by relatively cold secondary air blowing radially through the rotor-stator-wheel space. The interaction between the sealing flow and the main gas flow however causes aerodynamic losses. These losses as well as the secondary compressor air should be kept at a minimum in order to increase the efficiency of the whole machine. The Hot-Acoustic-Testrig (HAT) allows an investigation of the subject under realistic flow conditions. Therefore a specific measurement section has been designed, which features a plenum to provide secondary air to the main flow. To simulate an pressure increasing combustion, a setup with 6 fast shifting valves was realized. The unsteady flow was measured by pressure tabs with a high time resolution. In the next step a characteristic linear cascade was designed to replace the turbine stator and generate a typical stator wake. Measurements of the total pressure loss over the cascade vanes have been conducted by means of a five-hole probe and by Particle Image Velocimetry. A considerable pressure loss inside the vane wake was observed at a Mach number $Ma = 0.35$. The investigation is a subproject of the Collaborative Research Center 1029 *Substantial efficiency increase in gas turbines through direct use of coupled unsteady combustion and flow dynamics* and gives an outlook to further steps.

Keywords: Turbine ● Hot Gas Ingestion ● Secondary Air ● Unsteady Pressure Measurements ● PIV

1 Introduction

Gas turbine engines are widely used for energy conversion. They are employed for various applications, e.g. in power generation, propulsion systems and auxiliary power units. The overall efficiency of a gas turbine is about 40%; with 60% of the utilized primary energy is lost in form of heat. The gas turbine works with an isobaric combustion which slowly reaches its limits. It is commonly known that only a concept change will allow a significant increase of efficiency. An approach is to apply constant-volume combustion, realized by classical pulsed detonation as well as with a shockless explosion concept. Several consequences arise when applying a pulsed combustion. The individual engine components have to handle the pressure fluctuation resulting from the pulsed combustion. The challenges are e.g. the turbine cooling and the sealing against hot gas ingestion in turbine rim seals and a reliable operation of the compressor. The rim sealing is crucial to avoid hot gas ingestion between the stator and rotor in the inner machine. Otherwise, the hot gas ingestion will drastically reduce the lifetime of the disk and can even lead to a complete burst. In conventional gas turbines the rim sealing is realized by rotor-stator-cavities at the inner platform of the turbine vanes. The cavities are fed by secondary air which is extracted at the last stage of the compressor.

In the cavities, there are highly unsteady mixing processes due to the in and out coming flow. This leads to a high frequency interaction of the flow with different temperature and pressure levels in a very small geometry. In the last years, there have been investigations into the rim sealing. Chew et al. [1, 2] have studied the minimal required mass flow for the sealing as well as the flow in the cavities. Other researchers focused on the mixing processes between the annulus and the cavities [3, 4]. Furthermore, the relevance of the highly unsteady phenomena of the mixing processes has been underlined by Boudet et al. [5]. Pau et al. performed experiments at a transonic turbine stage and showed the influence of the sealing air in the annulus. Until now, there have been no publications about the influence of the pulsed detonation on the rim sealing. Therefore, there is a significant need to develop further conventional and innovative sealing concepts which are adapted to the influence of pulsed detonation combustion. One particularity in a pulsed detonation engine is the pressure increase throughout/in the combustion. As a result, the secondary air is extracted behind the combustion chamber which is expected to raise efficiency and decrease fuel consumption. Furthermore the impact of the pressure fluctuation on the rim sealing has to be investigated. A detailed understanding of the interaction of the main flow and the secondary air is necessary. Hence, a systematic study of the new consequences rising from the pulsed detonation combustion is indispensable. To realize those experiments, a Hot-Acoustic-Test Rig (HAT) has been designed to represent conditions similar to a turbine. With the HAT it is possible to examine the interaction between the main and the secondary air flow under conditions close to those in reality. Pressures up to 10 bar and temperatures up to 820 K can be reached in the test section. The study is part of the Collaborative Research Center 1029 *Substantial efficiency increase in gas turbines through direct use of coupled unsteady combustion and flow dynamics* at Technical University of Berlin.

At the moment the focal point within the project is to design a test section where the influence of the pulsed detonation combustion on the turbine rim sealing can be studied. However, the overall aim of the Collaborative Research Center is to extend the test section such that new innovative cavities, which are adapted to pulsed detonation combustion, can be developed and researched. The present paper will introduce the test facility, the hot acoustic test, as well as the design of the test section. Furthermore, measurements of the pressure fluctuations and their influence on the turbine cascade in the HAT are shown.

2 Test Facility

HAT is a modular test facility for the investigation of acoustic and aero-thermal phenomena on liner and other thermally stressed surfaces in aero engines. This novel test rig is a joint facility of DLR and TU Berlin. The HAT provides the possibility of steady or unsteady flow conditions, with controlled high pressure and / or high temperature environments. In addition, a secondary cooling air supply is installed, which can be used to simulate a secondary air flow. An overview of the main characteristics is shown in Table 1.

Parameter	Variable	Value
max. temperature	T_{max}	820 K
max. pressure	P_{max}	1100 kPa (abs)
frequency range	f	160 – 2800 Hz
max. total mass flow rate	$\dot{m}$	0.78 kg/s
Mach number	Ma	0 – 0.7
duct diameter	d	70 mm

Table 1. Hot-Acoustic-Testrig parameters

The air for the HAT facility is provided by two rotary screw compressors that can deliver a total mass flow rate of 0.78 kg/s. The air is dried (at a dew point of 276 K), filtered, and then delivered into a 2 m^3 pressure reservoir at a temperature of 288 K at 1600 kPa of pressure. After the reservoir the pressured air is divided into the main duct and a terminal for secondary air. With the main flow entering an electrical air heater, it can increase the temperature of the flow to any value between ambient and 820 K. An overview of the facility and its main components is shown in Figure 1.

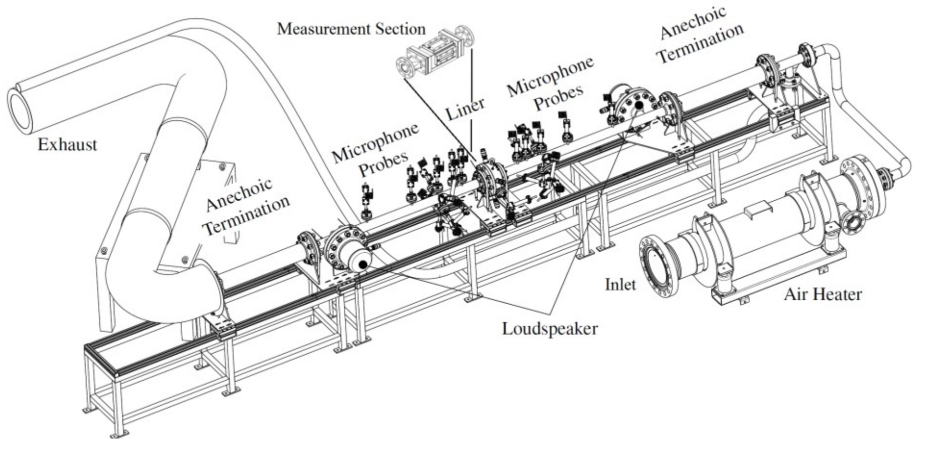

Fig. 1. HAT overview

Following the air heater is a modular duct system with a 70 mm diameter. While the measurement section is located at the center, microphone probes and loud speakers are arranged up- and downstream. The thermo acoustic setup is described by Knobloch and Lahri et al. [6, 7].
The liner bias flow, e.g. cooling flow and/or secondary air flow is delivered at a temperature of 288K at 1600 kPa of pressure. The supply for each consumer can be set individually via mass flow controllers. The flow rate and pressure in the duct is controlled via a pressure valve, a volume flow meter, and a nozzle at the end of the test duct behind the downstream anechoic termination (see also Figure 1). The pressure in the duct can be adjusted continuously between ambient and 1000 kPa absolute pressure. Then, the resulting flow velocity in the duct is defined by the geometry of the nozzle and can be determined by the laws of gas dynamics. Raising the pressure in the duct increases the flow velocity until a critical pressure is reached. At the critical pressure the velocity in the nozzle equals the speed of sound Ma = 1. For pressures beyond the critical pressure, the velocity remains constant.
The critical pressure in the duct p_1^* can be calculated from the isentropic relation for the pressure see [7] (Lahiri et al.).

$$\frac{p_2}{p_1^*} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma+1}} \tag{1}$$

with the index 1 denoting the quantities in the duct and 2 beyond the nozzle. The nozzle back pressure p_2 equals the ambient pressure. As the heat-capacity-ratio has a value of γ = 1.4, the critical pressure can be given as p_1^* = 191.8 kPa at p_2 = 101.325 kPa. Including the continuity equation Lahiri [7] formulates the following equation for the Mach number

$$\mathrm{Ma}_1 = \frac{A_2}{A_1}\sqrt{\frac{2}{\kappa}}\,\Psi \tag{2}$$

This allows the plotting of the Mach number characteristics of the HAT. Figure 2 shows the characteristics of five nozzles at diameters between Ø15mm - Ø55mm at a temperature of 293K (on the left) and 773K (on the right). The theoretical predictions based on Equations 1 and 2, displayed as lines, and the measured values, displayed as markers, agree very well.

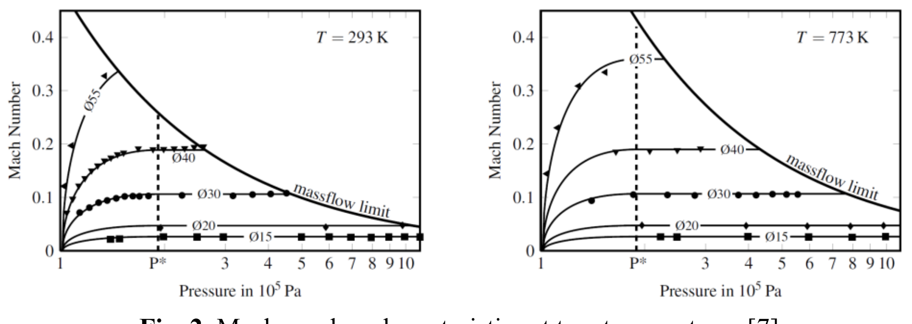

Fig. 2. Mach number characteristics at two temperatures [7].

3 Experimental Setup

3.1 Generation of a pressure fluctuation

In order to evaluate the impact of the unsteady combustion on the sealing between turbine rotor and stator, it is necessary to create an pressure fluctuation. There are two projects within the Collaborative Research Center 1029 which address the Shockless Explosion Combustor (SEC) as well as the Pulse Detonation Engine (PDE). Unlike the PDE, the SEC concept lacks a detonation wave. That causes smaller pressure amplitudes, while the combustion frequency is between 10 – 150 Hz for both applications, Roy et al [8]. Caldwell, Caldwell & Gutmark [12] describe the influence of a pulsed detonation on the turbine. A detonation wave caused by a pulsed detonation combustor would run into the turbine stator. The flow is decelerated by the verticle shock wave and/or expansion, so that there will be an unsteady main flow across the rotor-stator-cavity. The aim is to induce such an pressure fluctuation across the cavity area into the HAT-measurement section. This rectangular module with cross section of 90 mm x 43 mm is described in [9].
In order to examine the effects of these different combustion technologies, it is necessary to develop a setup were the pressure amplitude and animated frequency can be adjusted. For this reason, and because of the periodic character of the combustion, a setup using fast switching valves is chosen. Other experimental setups were considered, but rejected e.g. shock-waves-tube and acoustic actuation via speakers. A shock-wave-tube can only generate a single event and no periodic fluctuation, while loudspeakers would need a huge amount of power to create the required pressure amplitude and are difficult to integrate into such a small rig. Only the main flow is exposed to a periodic fluctuation, cause there will be the biggest impact, the secondary air remains at a steady state.
The secondary air supply of the test facility provides the possibility to adjust the pressure amplitude to the required settings. In addition a setup including 6 electromagnetic valves (Festo MHE4) is used to insert the pressure fluctuation with the appropriate frequency. The valves are fed by the air supply via a pressure controller and a small pressure tank to contain a consistent pressure. Controlled by a frequency generator the valves are able to work at a switching frequency up to 250 Hz.

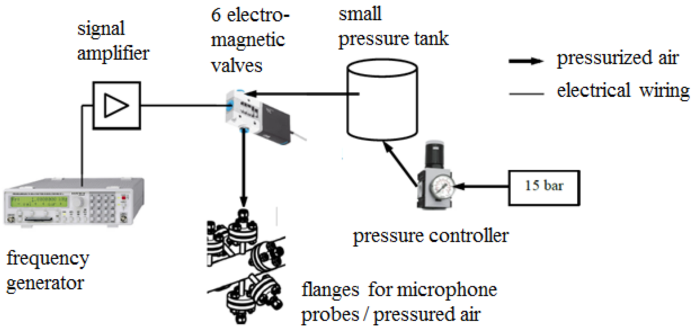

Fig. 3. Setup for the pressure actuation

They are mounted on the rig through 6 microphone flanges with a 6 mm diameter. Figure 3 shows the assembly of every actuator component and its wiring.
The valves are located approximately 0.7 m upstream the measurement section (see Fig. 4), as they insert the pressure fluctuation vertically into the flow. Through the high turbulence inside the rig, the additional air is mixed with the main flow before entering the measurement section. The nozzle-like duct transfers the flow into the main section with dimensions of 90 mm x 43 mm. A three-side optical access is available, as well as a mounted plenum on the bottom of the section. This plenum features boundary layer suction at the section inlet and an inlay construction, which can adapt liner configuration, measurement probes and secondary air, if needed. A flat plate was used in this investigation, mounted with 2 rows of 4 differential pressure tabs (Sensortechniques HDO series). The used pressure sensors have a measuring range up to 1000 mbar and a relative error of max. ±0.5% Full Scale Output (FSO). All 8 signals were obtained simultaneously at a sampling rate of 1 kHz, using a 64-channel signal amplifier. In order to avoid aliasing, a hardware low pass filter at 100 kHz was used before sampling. The record time was 120 s for each set point.

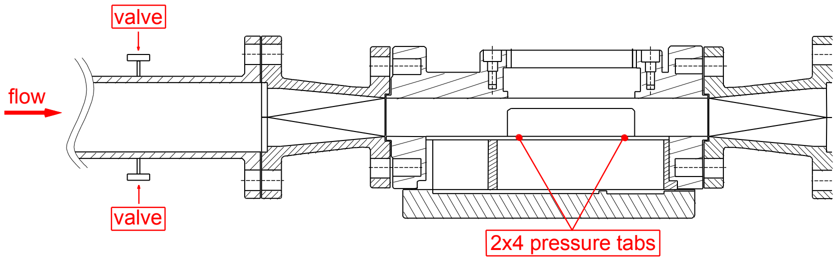

Fig. 4. Profile of the duct and measurement section

3.2 Turbine Cascade

Dimensioning

An analytical dimensioning of a plane cascade was executed to create a turbine-like wake. This is necessary to get a typical alternating pressure distribution at the sealing cavity, which triggers the sealing flow/main flow interaction as described by Phadke and Owen [10]. The cascade idealizes a turbine stator row downstream of the combustion chamber, with the first stator profiles refer as vanes or inlet guide vanes. A cascade with 3 straight profiles is chosen. Real turbine profiles with a high deflection of the flow cannot be used, because of the small size of the measurement section and its geometry. For the same reason, the separation angle λ has to be zero degrees. This adjustment means a strong simplification compared to a real turbine stator row, because there is a nozzle/diffusor-like passage which accelerates the flow. But this adjustment has to be made, because of the facility layout. Nevertheless this is acceptable, while the focus of the investigation is the influence of the pressure fluctuation on the sealing flow. A symmetrical NACA0020 airfoil as depicted in Figure 5 is used for the experiments. The parameters of the airfoil are shown in Table 2.

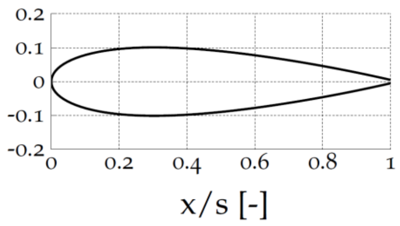

Fig. 5. NACA0020 airfoil

Parameter	Value
Span	s = 20 mm
Mach number	Ma = 0.35
Frequency range	f = 40 – 80 Hz
Pitch-to-chord ratio	t/c = 0.75
Strouhal number	Sr = 0.01 – 0.02

Table 2. Properties of the turbine cascade

A pitch-to-chord ratio of t/c = 0.7 – 0.8 is the actual value for an impulse turbine and the Mach number behind the combustion chamber is around Ma = 0.3 – 0.4 [11]. The Strouhal number, a dimensionless number used to describe oscillating flow mechanisms, has been used to determine to blade span, as depicted in equation (3)

$$s = \frac{Sr \cdot u_{\infty}}{f} \tag{3}$$

While the frequency range of the combustion is estimated to be at f = 40 – 80 Hz, the Strouhal number is Sr = 0.01 – 0.02 for a turbine environment. The upstream velocity u_∞ can be calculated by the Mach number

$$u_{\infty} = Ma_{\infty} \cdot \sqrt{\gamma R T} \tag{4}$$

were the heat-capacity-ratio has a value of γ = 1.4 and the gas constant R = 287.058 J/kg K. A possible operating point of the HAT lies at Ma = 0.35 and T = 773 K, as shown by Lahiri et al. [7] and in Figure 2 (right). This results in a span for the vane of s = 20 mm. Figure 6 shows the operating frame for the chosen airfoil.

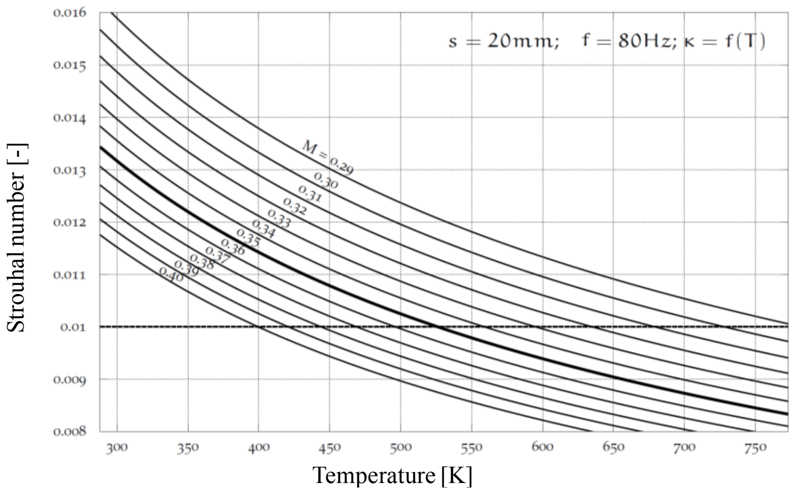

Fig. 6. Strouhal number over temperature range

The resulting airfoil allows an investigation on the designated Mach number for a cold or hot flow. A span of s = 20 mm was chosen, because a span over s = 20 mm would lead to a blockage of the flow, while a smaller profile would lead to a smaller wake.

Experimental setup

To investigate the wake-generating cascade, a related setup as in section 3.1 is used, that no valves are being used upstream. In addition to the pressure tabs a five-hole-probe is used to survey the cascade wake. The vanes are attached to the plenum cover as shown in Figure 7.

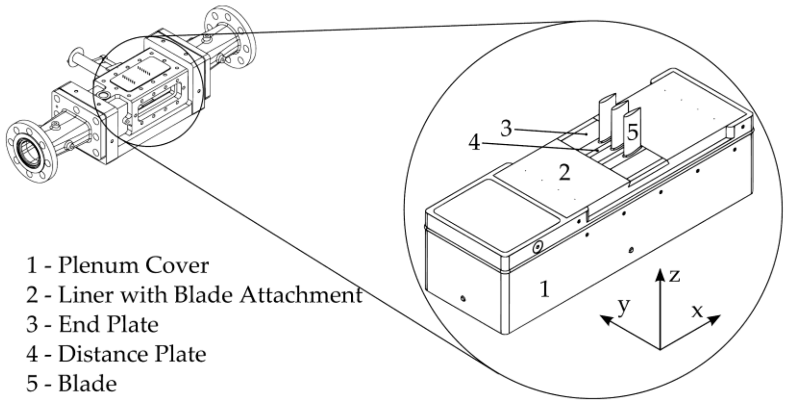

Fig. 7. Measurement section with integrated plenum cover

The five-hole-probe is located 1/3 of the blade span behind the vane. This is the area were the rotor-stator-cavity is located (see Owen et al. [10]). The probe covers a straight line on the y-axis at heights of 9 mm, 11.5 mm, 16.5 mm and 21.5 mm bottom up, with the last value corresponding to half of the sections total height. The described assembly is shown in Figure 8. The five-hole-probe is connected to the HDO-Pressure-sensors, with the same characteristics as in sec.3.1. Since the test rig is under pressure, there are two sealed window configurations, with a total of four probe holes shared.

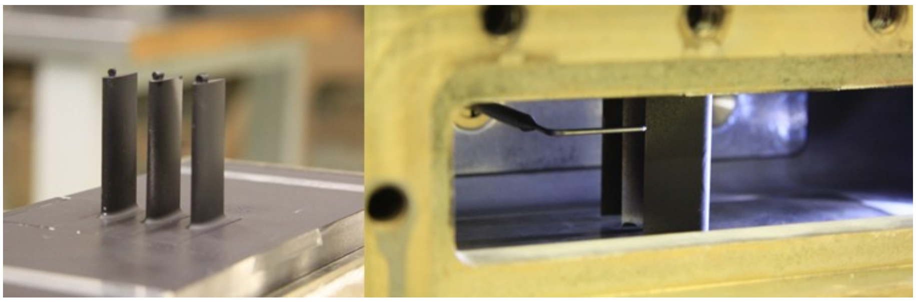

Fig. 8. Wake cascade (left) and inside the testrig with a five-hole-probe (right)

Additionally, Particle Image Velocimetry (PIV) is used to verify the pressure measurements and to characterize the flow field. A planar 2D-PIV setup is adjusted in planes tangential to the main flow velocity. The measurements were performed with a pair of Neodym-YAG Lasers, which emit laser beams at a wave length of λ = 532 nm, and a LaVision ImagerProX CCD camera with a resolution of 11 Mpx. The PIV setup is shown in Figure 9. The light sheet is coupled into the passage from upside, the measurement section through a window, while the camera view is normal to the light sheet. Titanium dioxide (TiO_2) The average particle size of the seeding is.

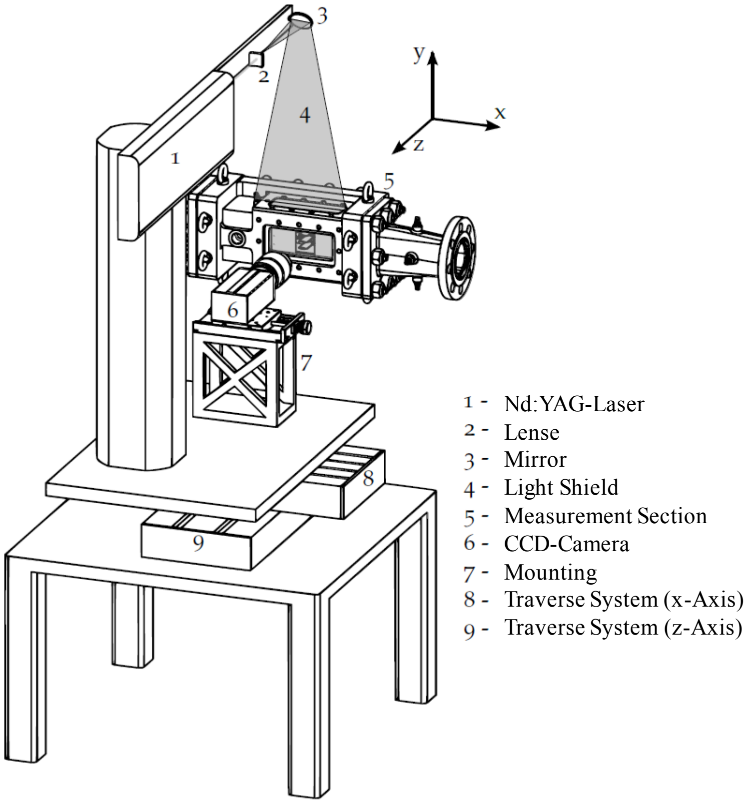

Fig. 9. PIV setup

The recorded double frame images are post processed with the Davis 8 software of LaVision. An adaptive cross correlation algorithm is used with interrogation window shifting and deforming. Evaluation started with a 64 x 64 px^2 window and was reduced to a final size of 16 x 16 px^2 in a spatial resolution of 0.76 mm. Bandpass and median filters are used to reduce the rate of outliers < 2.5% and the filtered vectors are interpolated.

4 Results

4.1 Pressure fluctuation

The measurements were carried out for two Mach numbers (*Ma* = 0.1 & *Ma* = 0.35) and temperatures around 288 K, while the supply pressure of the valves was varied from p_v = 7 bar (abs) up to p_v = 12 bar (abs). In Figure 10 the time-resolved behavior of the pressure probe signal is depicted.

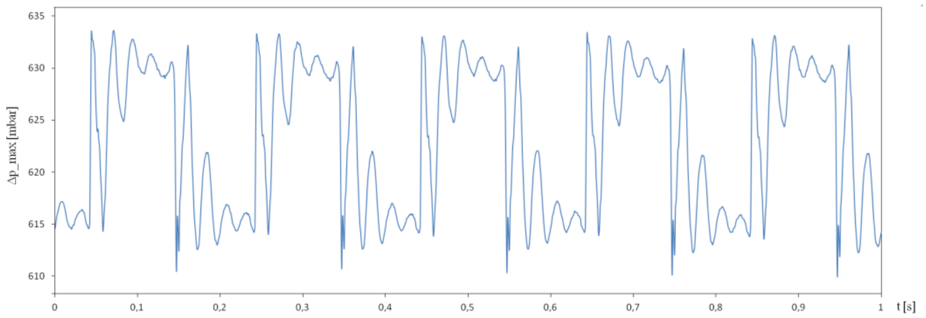

Fig. 10. Average pressure fluctuation for all 8 probes at *f* = 40 Hz

A square-wave-signal is approximated. Through the instant character of the noise/ pressure impulse the actual pressure inside the measurement section oscillates around the signal value given by the frequency generator. Figure 10 shows the peak-to-plateau values for a recording time *t* = 1 s at a frequency *f* = 40 Hz for both locations of the pressure probes. No phase deviation between the two measurement-/probe-locations is detected.

Results at Ma = 0.1

Figure 11 shows the averaged peak-to-plateau value of the pressure fluctuation over valve frequency at *Ma* = 0.1. It is recognizable that the pressure amplitude increases with rising supply pressure. The highest pressure amplitude is p_{max} = 130 mbar at *f* = 40 Hz, which results in a relative pressure gradient of 8% compared to the absolute pressure of the main flow. A frequency of *f* = 40 Hz has been chosen for the pressure fluctuations, because at this frequency the highest pressure amplitudes are reached. In literature Roy [8] states a pressure raise from 10 - 20%, but a pressure increase up to 30% is targeted within the Collaborative Research Center. So it is essential to gain a higher pressure amplitude which will be incorporated in the future. This can be achieved by doubling the number of valves from 6 up to 12 via a Y-Mounting. By doing that it is possible to increase the mass flow and therefore the pressure amplitude at parallel operation, or the increase the frequency at serial operation. Another obvious method would be a shock tube. This would provide a higher pressure amplitude, but the downside of this technique is it's singularity; with a shock tube setup it is not possible to investigate the periodic effects of the flow.

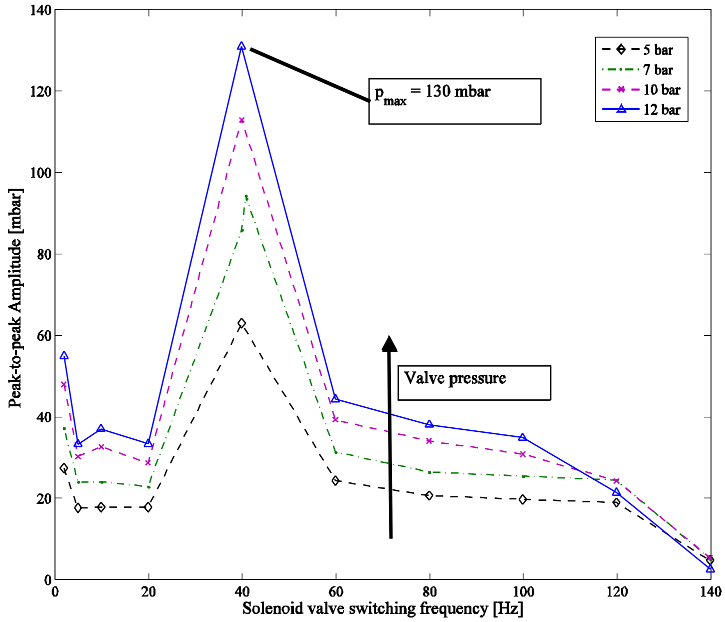

Fig. 11. Pressure amplitude over valve-switching frequency at *Ma* = 0.1

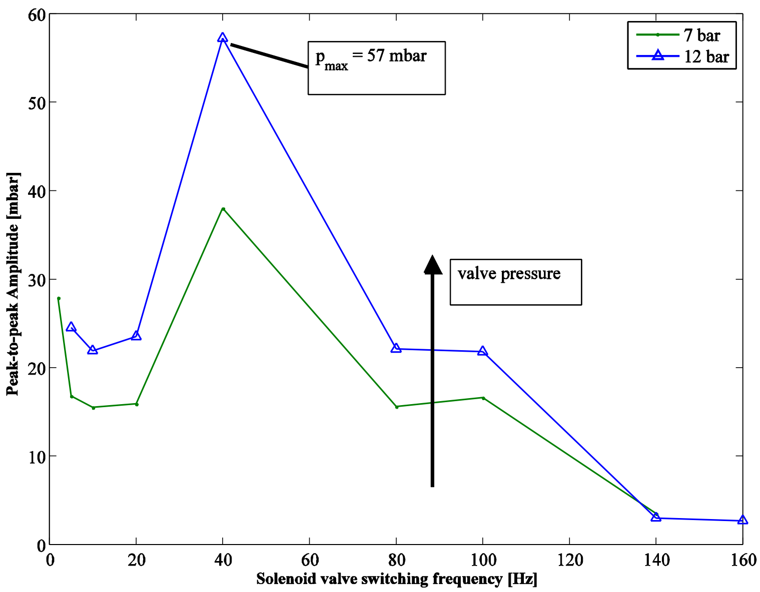

Fig. 12. Pressure amplitude over valve-switching frequency at *Ma* = 0.35

Results at Ma = 0.35

In Figure 12 the results for Ma = 0.35 are depicted. The peak pressure is at p_{max} = 57 mbar, with a frequency of f = 40 Hz, and maximum pressure gradient of 4.2% relative to the main flow. It is recognizable that p_{max} decreases with higher Mach numbers. This circumstance can be explained by the influence of the inserted mass flow through the valves in relation to the main mass flow. At a low Mach number the inserted mass flow has a bigger impact on the relatively low mass flow of the main flow. While at higher Mach numbers associated with a higher mass flow, the impact of the inserted mass flow decreases.

From a frequency of f = 140 Hz and beyond, the measured pressure was very small and lies within the measurement error.

4.2 Turbine cascade and wake generation

Time averaged pressure measurements featuring a five-hole-probe and pressure tabs have been performed, to determine the position as well as the losses of the generated wakes. For a steady-state flow with Mach number Ma = 0.35 and a temperature of T = 288 K, the probe was traversed behind the vane profiles in 0.5 mm steps at 4 different heights. Figure 13 shows the average pressure losses inside the wake related to the pressure upstream of the cascade.

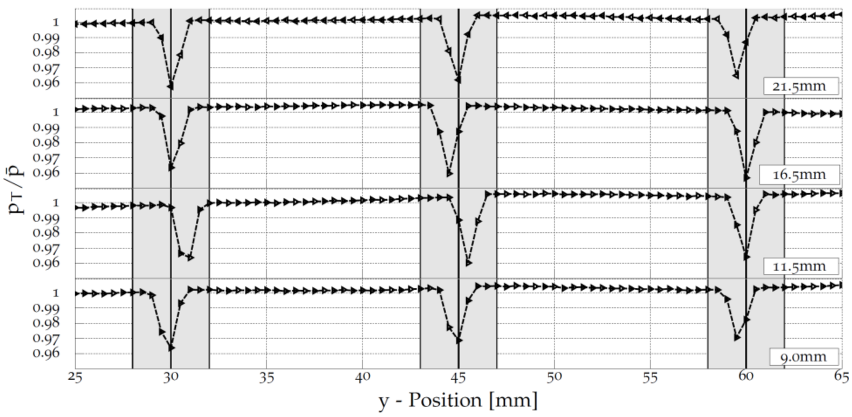

Fig. 13. Normalized average pressure losses behind the cascade

Additionally PIV Measurements of the wake were performed to determine the velocities in mean flow direction. Figure 14 shows that the middle vane has a slightly higher velocity loss in wake than the outer vanes.

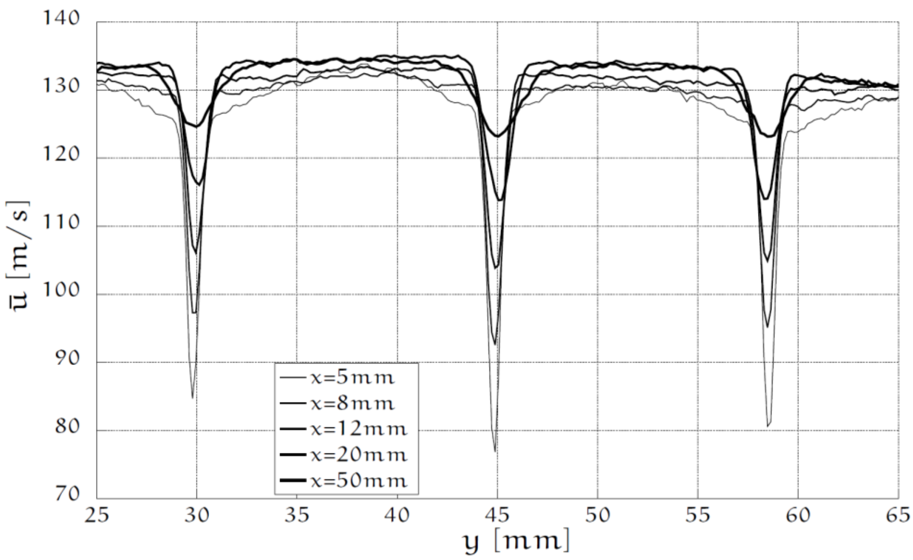

Fig. 14. Time-averaged velocities at Ma = 0.35 mid span position (z = 21.5 mm)

In Figure 14 the time averaged velocities in the wake are depicted for distances from x = 5 mm up to x = 50 mm behind the cascade. The velocities are calculated from PIV data and are in a good agreement with the pressure data.
A closer view behind one of the outer vanes is shown in Fig. 15. Velocity vectors reveal a tendency to the left direction (stream wise). This is highlighted by the velocities $\overline{v}$ normal to the flow. This change of direction is unexpected and can be explained by slower velocities near the wall of the measurement section.

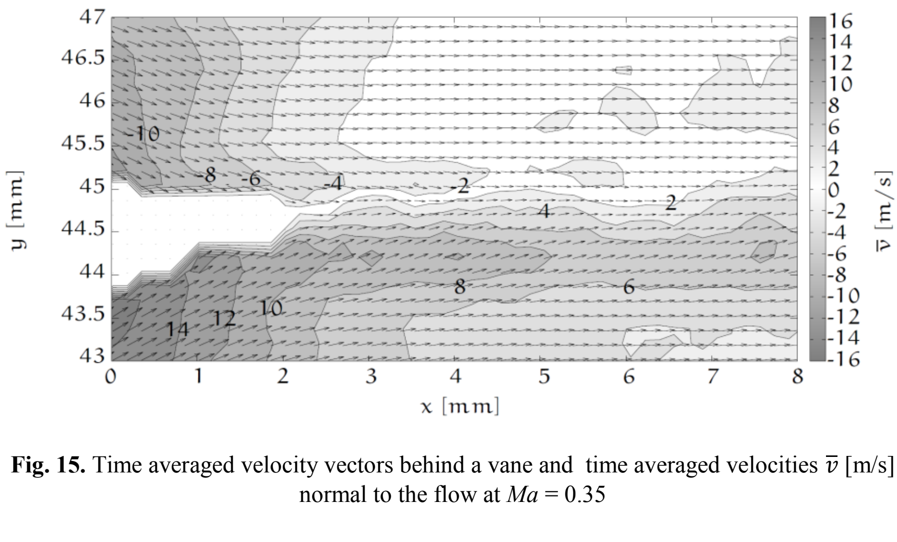

Fig. 15. Time averaged velocity vectors behind a vane and time averaged velocities $\overline{v}$ [m/s] normal to the flow at Ma = 0.35

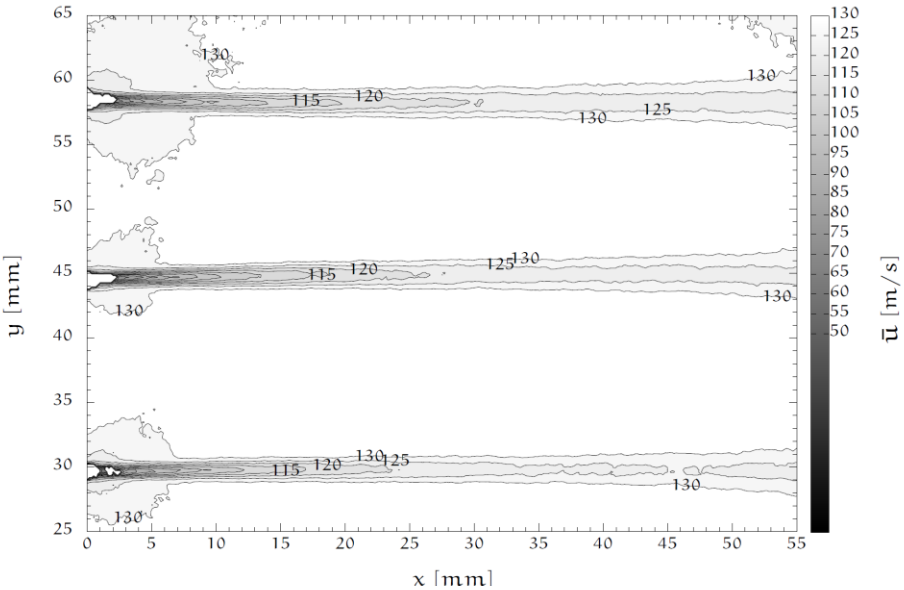

Fig. 16. Time averaged velocities (absolute) behind the cascade at *Ma* = 0.35 (mid span)

It can be recognized that the designed cascade produced a wake behind the vanes with a thickness of about 50% of the vanes' thickness. The normalized pressure loss is at max. 4-5% of the upstream flow. In [13] Bunker et al., a pressure loss of around 10% is measured in a rotating setup with realistic vane profiles. Considering the geometrical limitations of the HAT-measurement-section, a 5% pressure loss is acceptable. The use of bigger vane profiles would lead to a larger wake / pressure loss, but also to a blocking of the flow.

5 Summary and Conclusion

The Hot-Acoustic-Testrig has been used to investigate a setup to create an pressure fluctuation and the generation of turbine-like wakes. The rig enables a realistic machine environment in terms of Mach number, pressure and temperature. As a first step within the research work, pressure measurements were performed. A setup to add an pressure fluctuation into the main flow was developed and successfully tested. The setup produced positive pressure gradients up to 8% of the main flow at a frequency f = 40 Hz and a Mach number of Ma = 0.1 as well as a pressure gradient of 4.2 % at a frequency f = 40 Hz and a Mach number of Ma = 0.35. It was observed that the pressure gradient decreases if the Mach number goes up and/or the valve frequency raises over 40 Hz.

The pressure fluctuation in the secondary air was neglected within the experiment, even though it is expected that there were be unsteady flow phenomena upstream the

combustion chamber, due to the pulsed detonation combustion. The influence of combustion (PDE/SEC) on the compressor flow is still under investigation.
A linear cascade was designed to generate profile wakes, which interact with the sealing flow around the turbine cavity. Three symmetrical profiles (NACA0020) were fitted to the flow-, facility- and combustion conditions. Pressure and PIV measurements showed a wake with a maximum total pressure loss of 5% behind the profiles.
In a next step, the influence of the pressure fluctuation on the cascade wake should be investigated, before implementing a cavity behind the cascade for main flow / sealing flow interaction.

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Nomenclature

A	[m^2]	Cross-section area
Ψ	[--]	Discharge of the fluid
λ	[°]	Separation angle
γ	[--]	Heat-capacity-ratio
d	[mm]	Diameter of the duct
f	[Hz]	Frequency
$\dot{m}$	[kg/s]	Mass flow
Ma	[--]	Mach number
p	[kPa]	Pressure
p^*	[kPa]	Critical pressure
p_v	[kPa]	Pressure of the valve supply
s	[mm]	Vane span
Sr	[--]	Strouhal number
t	[s]	Recording time
t/c	[s]	Pitch-to-chord ratio
T	[K]	Temperature
u	[m/s]	velocity (x-axis)
$\bar{u}$	[m/s]	average velocity (x-axis)
v	[m/s]	velocity (y-axis)
$\bar{v}$	[m/s]	average velocity (y-axis)

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