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A COUPLED STEADY-UNSTEADY-STATE DATA ACQUISITION SYSTEM FOR THE INVESTIGATION OF ROTATING INLET DISTORTIONS AT A MULTI-STAGE COMPRESSOR TEST FACILITY

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ABSTRACT

In a twin-spool jet engine the HP-compressor is subjected to a rotating inlet distortion if rotating stall in the upstream LP-compressor occurs. This destabilizing effect on the compressor operating behavior may lead to HP-compressor instability like rotating stall or surge. Studies on compressor flow instabilities are carried out at the multistage compressor test facility with the 5-stage HP-compressor Rig212. In order to investigate this specific type of unsteady inlet distortion the compressor is operated with a distortion generator in the inlet duct performing a rotating inlet distortion with variable speed of rotation up to 60% of the compressor design speed.

Kulite high frequency pressure sensors as well as hot-wire probes are installed to resolve the unsteady character of the inlet distortion and to analyse the stall inception process. The conventional steady-state instrumentation consists of static pressure taps, thermo-couples, and total pressure combs. Coupling these independent PC-based measurement setups to one combined system with up to 14 fast and up to 64 slow data acquisition channels provides measurements with exact time reference but various data sampling rates and sensors, respectively.

NOMENCLATURE

Symbols:

c	[m/s]	flow speed
$\dot{m}$	[kg/s]	massflow
n	[rpm]	speed of rotation
p	[Pa]	pressure
q	[Pa]	dynamic pressure
DC	[-]	distortion coefficient
T	[K]	temperature
ρ	[kg/m^3]	density
φ	[°]	sector angle
Π	[-]	total pressure ratio

Subscripts:

compr	compressor
dist	distortion
red	reduced
t	total conditions
undist	undistorted

Subscripts:

-	averaged

Abbreviations:

LP	low pressure
HP	high pressure

INTRODUCTION

Previous work on the compressor test facility by Jahnen et al. [1,2] investigated the influence of steady-state total pressure and swirl inlet distortions showing the strong influence of different loading patterns on the stable operating behavior and stall inception of the compressor. In the past the effects of rotating inlet distortions were investigated by Longley et al. [3] who carried out experiments on a 4-stage low-speed research compressor (500 rpm) with four different blade configurations. The experimental setup was equipped with a rotating wire mesh screen 1.5 radii upstream of the IGVs rotating at various speeds co- and counterclockwise with the rotor. Two tested bladings exhibit modal-type stall inception with a significant loss of surge margin at a screen rotation rate of 0.5 fraction of rotor speed whereas the other two configurations showed spike-type behavior with a substantial decrease in surge margin at 0.3 and 0.7 screen rotation rate.

The present research work focuses on the influence of rotating inlet distortions on the stable operating behavior of a high speed jet engine compressor rig and the detection of its aerodynamic eigen-frequencies as well as the analysis of the stall inception process.

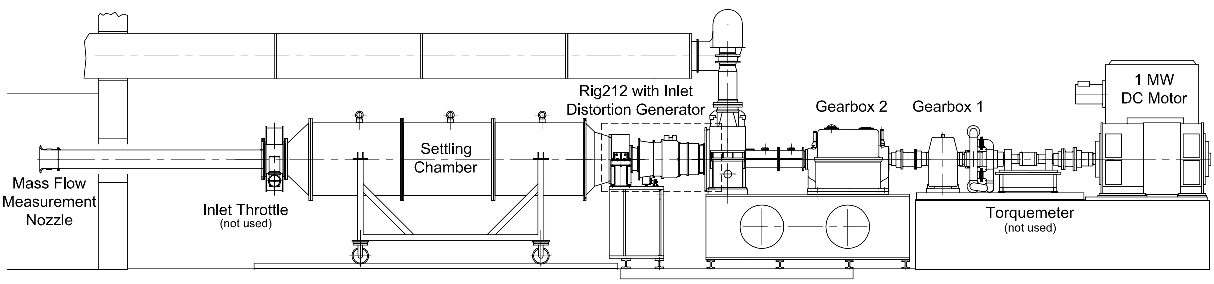

Figure 1: Multi-stage compressor test facility with new experimental setup

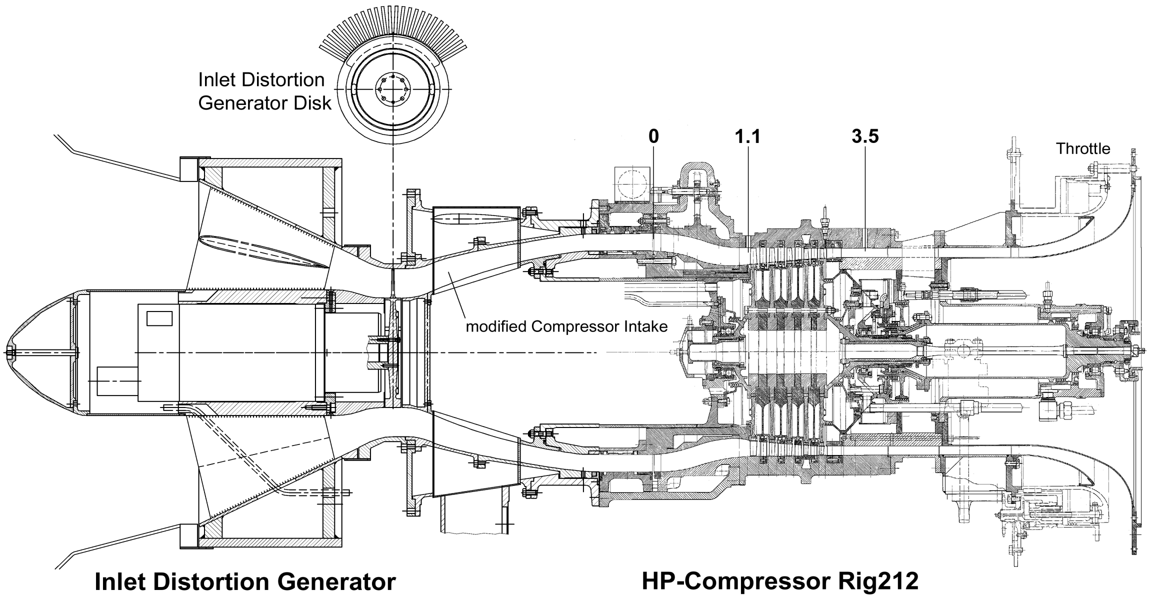

Figure 2: Experimental setup

EXPERIMENTAL SETUP

The compressor under investigation is the 5-stage HP-compressor Rig212 of the European Turbo Union RB199 jet engine development program. For the three-spool RB199 a 5-stage HP /4-stage IP and a 6-stage HP / 3-stage IP compressor configuration were investigated and the latter one selected for the production engine. The Rig212 remained in research service until 1975 and then was mothballed. At last the compressor has kindly been given to the Universität der Bundeswehr by the MTU Munich for basic research purposes at the Institut für Strahlantriebe. Under ISA test conditions the compressor provides a mass flow of 4.68 kg/s and a total pressure ratio of 2.87 at 13860 rpm design speed. A bleed behind the 3rd stage reduces the mass flow by 3 percent. The hub to tip ratio varies from 0.84 in the first rotor to 0.90 in the last stator. Each compressor stage is designed for axial inlet flow, the rotor blades are DCA profiles and the guide vanes NACA 65 profiles. At the design point condition the relative inlet Mach number of the first rotor is 0.86 at the mean radius, which is 168.6 mm. The compressor design is still representative of the HP-compressors found in current aircraft engines.

Driven by a 1 MW DC motor the Rig212 is installed in an open circuit test facility. Filtered atmospheric air is supplied through a mass flow measurement nozzle and a settling chamber. Downstream of the compressor the air flow is controlled by a throttle device - the small exit plenum prevents the occurence of surge if the compressor stalls. A detailed description of the multi-stage compressor test facility is given by Jahnen and Fottner [4]. Figure 1 shows the actual status of the facility. The major modification can be found upstream of the compressor rig with the new rotating inlet distortion generator and its rack. The compressor design allows the positioning of a rotating device only upstream of the whole rig as displayed in Figure 2. A high flow speed is required in the distortion generator disk plane to produce a relevant total pressure distortion. Therefore the compressor intake had to be modified by reducing the casing radius providing a decent acceleration through the whole compressor inlet duct. Measurements without the upstream inlet distortion generator have revealed that a slightly higher total pressure loss of the new intake and a minor change in the radial total pressure distribution affect the surge line only marginally.

Figure 3 gives a detailed view on the rotating inlet distortion generator disk. The design had to take into account the centrifugal forces at high speed of rotation. Therefore the disk is a one-piece unit with a minimized hub diameter of 191.6 mm. 26 bars with a rectangular profile are positioned in a 120°-sector on the circumference to produce a sectorized total pressure loss. Each bar is 50.2 mm long and 5 mm wide in the front view with a 6 mm wide base and 4 mm wide tip in the profile. To avoid aerodynamically induced flutter of the distortion generator bars the flow speed i.e. the compressor shaft speed is limited to 93.3 % design speed (12930 rpm). For the balance of the disk the rim of the undistorted 240°-sector is much thicker. Additionally balance weights are mounted in a ring slot to provide proper balancing. The disk is driven by a 19 kW AC motor with a maximum shaft speed of 9000 rpm (150 Hz) i.e. 65% of compressor design speed. Six radial struts contain the power and cooling water lines for the drive and center the drive-disk unit upstream of the compressor intake. The nozzle-like outer casing accelerates the flow and provides good stiffness. The whole distortion generator is installed on a rack between the settling chamber and the compressor rig. The flow duct is sealed with rubber sleeves that allow thermal elongation of the compressor.

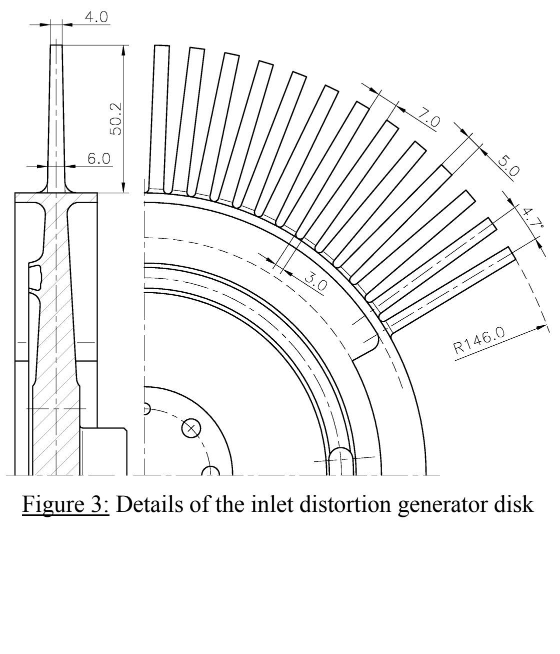

Figure 3: Details of the inlet distortion generator disk

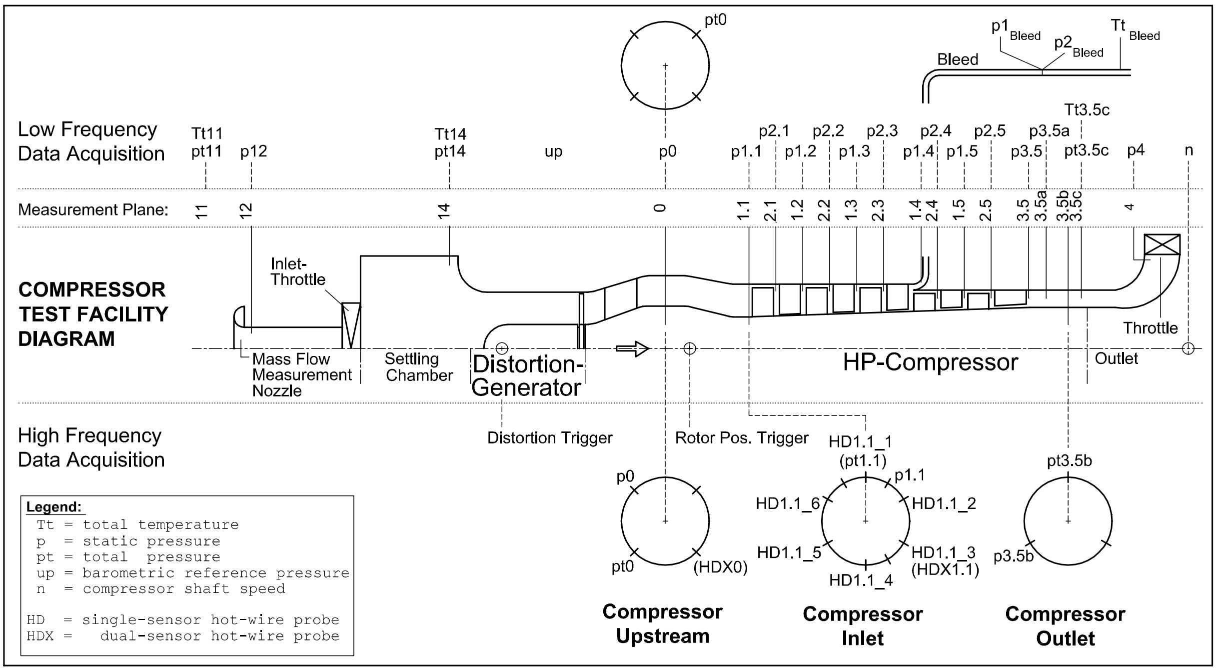

Figure 4: Instrumentation of the test facility and the compressor

INSTRUMENTATION

The instrumentation of the Rig212 and the axial compressor test facility is shown in Figure 4 and can be classified into a low and a high frequency i.e. steady-state and unsteady-state part according to the frequency response of the sensors.

Low Frequency Instrumentation

The mass flow of the compressor is determined with a calibrated mass flow measurement nozzle, the bleed mass flow is measured with an aperture. Several static pressure taps around the annulus are available: Twelve taps in the compressor upstream plane *0* on the hub, twelve taps each in the compressor inlet plane *1.1* on hub and casing, six taps in the compressor outlet plane *3.5* on hub and casing, another eight taps in plane *3.5a* on hub and casing and six taps between each blade row (plane *2.1-2.5*) on the casing. The static pressure taps of each plane are pneumatically averaged with a ring line. Compared to the instrumentation used by Jahnen et al. [1,2,4] the static pressure resolution over the annulus is no longer available but also not useful due to the unsteady character of the inlet distortion. A new set of four equally spaced pressure taps is found just before the throttle (plane *4*). One single total pressure probe is located compressor upstream (plane *0*) on the mean radius, four total pressure combs with five radial distributed pitot tubes each are placed in the compressor outlet plane *3.5c*, each measurement radius is connected with a ring line. The total temperature in the settling chamber (plane *14*) i.e. the experimental setup inlet is determined with an array of Pt10 thermal resistors whereas the total temperature in the compressor outlet plane *3.5c* is measured by four total temperature combs with five radially distributed NiCr-Ni thermocouples. An inductive sensor on the compressor shaft provides a sine-signal with the rotor speed frequency. The voltage signals corresponding to the throttle setting and the effective power of the rotating inlet distortion generator disk propulsion are not mentioned in figure 4 but also part of the low frequency instrumentation.

High Frequency Instrumentation

A combination of hot-wire-sensors and Kulite pressure transducers represents the aerodynamic high frequency instrumentation: A single-sensor array equipped with six equally spaced hot-wire probes around the annulus is located in the compressor inlet plane *1.1*. All sensors (DANTEC 55P11) are placed 2 mm away from the casing in the flow field, the wire orientation is sensitive to changes in the axial flow speed. Additionally a cranked dual-sensor probe (DANTEC 55P64) can be placed in the compressor upstream (*0*) or inlet plane (*1.1*) and allows the determination of flow angles in circumferential direction. Compressor upstream (*0*) and in the inlet (*1.1*) and the outlet (*3.5b*) respectively one Kulite static pressure tap is found. One Kulite total pressure probe is located in the compressor outlet plane (*3.5b*) and another one in the compressor upstream position (*0*) or in the compressor inlet (*1.1*). All Kulite sensors are sealed gage type i.e. each sensor has a capsuled 1 bar reference. The pressure range as well as the compensated temperature range are adapted to the flow conditions in the intake duct and the compressor exit. The selected sensors are listed in Table 1.

sensor type	plane	pressure range	used range	comp. temp. range
XCW-093	p *0*	350 mbar	50%	–20 - + 35°C
XCW-093	p *1.1*	350 mbar	62%	–20 - + 35°C
XCQ-093	p *3.5*	1700 mbar	87%	+20 - +130°C
LQ-125	pt *0/1.1*	350 mbar	55%	–20 - + 35°C
LQ-125	pt *3.5*	1700 mbar	96%	+20 - +130°C

Table 1: Kulite pressure sensors

The dual-sensor hot-wire probe as well as the Kulite total pressure probes are mounted in sensor traverse units that allow traversing of the flow field in radial direction.

Furthermore a rotor position trigger gives information about the position of the compressor rotor referring to the flow probe positions. The inlet distortion trigger is important for the ensemble-averaging of the measurement data to get a representative picture of the rotating inlet distortion.

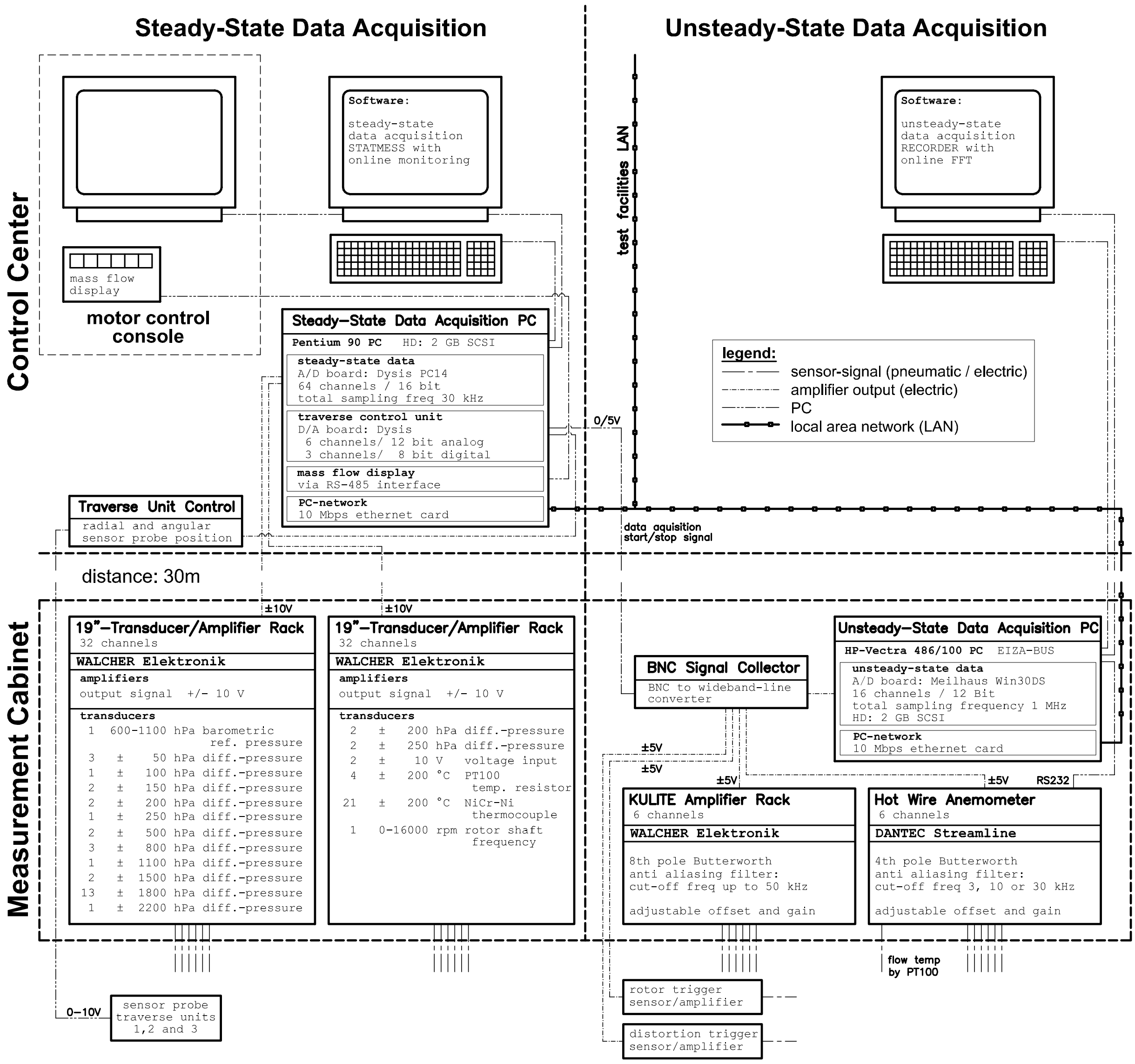

Figure 5: Coupled steady-unsteady–state data acquisition

DATA ACQUISITION

Figure 5 gives a comprehensive overview about the PC-based coupled steady-unsteady-state data acquisition. The setup is spatially divided in the measurement cabinet just beside the test facility i.e. compressor and inlet distortion generator and the control center about 30 m away. The PCs are connected with the local area network maintained by a Linux-fileserver.

Steady-State Data Acquisition

The steady-state data acquisition PC is equipped with one DYSIS PC14 A/D-board providing 64 channels for low frequency signals with 16bit resolution and ± 10V input. The data acquisition software STATMESS, written in Borland TurboPascal, operates the A/D-board with a fixed sampling rate of 100 Hz per sensor. The software allows an online monitoring of the compressor giving informations about selected measurement channels and the operating point in the compressor map. The compressor and bleed mass flow informations are transferred via an RS485-interface to the motor control console where the compressor speed and the throttle level are adjusted. The AD-board is connected via two 30 m long wideband-lines with the two Walcher Elektronik 19“-transducer/amplifier racks in the measurement cabinet. Each rack provides 32 channels by integrating 16 transducer/amplifier plug-in cards with two channels each. The amplifiers transfer the measurement range of the transducers to a ± 10V output signal matching the input requirement of the the AD-board. One channel is instrumented with a high precision barometric sensor whereas all other pressure transducers measure differential pressures with various measurement ranges as displayed in figure 5. For temperature measurements PT100 thermo resistor and NiCr-Ni thermocouple amplifiers are used. The compressor rotor speed is determined by an f/U-converter. The compressor throttle setting and the effective power of the rotating inlet distortion generator disk drive are available as voltage signals. More detailed information about the transducers and the accuracy and calibration of the measuring chain of the steady-state data acquisition is reported by Jahnen and Fottner [4].

The sensor probe traverse units are operated with a DYSIS six channel D/A-board. The selected analog voltage output corresponds to a certain radial or angular position of the probe in the flow field. Therefore each of the three available traverse units requires two D/A channels to adjust the radial position and the angle of the mounted probe. Because of the lack of necessity to change the probe angle of all traverse units one channel has been selected to start and stop the unsteady-state data acquisition using an analog voltage signal as described below.

Unsteady-State Data Acquisition

In contrast to the low frequency data acquisition setup the unsteady-state data acquisition PC with the AD-board is integrated in the measurement cabinet at the test facility to avoid high frequency signal damping due to long signal line lengths. The keyboard and the monitor in the control center are connected with signal line amplifiers. One Meilhaus Electronic Win30DS A/D-board is installed providing 16 channels for high frequency signals with 12bit resolution and a ± 5V input. The sample-and-hold concept of this AD-board provides exact time reference for each sample of all measured channels. The data acquisition software RECORDER from Walcher Elektronik, written in Borland TurboPascal, allows the data acquisition of 1 to 16 channels with different sampling rates up to 250 kHz per channel and a maximum total sampling rate according to the AD-board performance of 1 MHz. The sampled data are written directly on hard-disc managed by the EISA-bus system of the PC which provides the necessary data transfer rates. Therefore the measurement time is only limited by the free disk space. Brunner et al. [5] used the same data acquisition system for measurements inside the high-speed cascade wind tunnel where a wake generator induced the transition in turbine and compressor cascades. The data acquisition setup was modified to start the unsteady-state measurement if the voltage signal of the wake generator trigger is applied to channel 16. Additionally the number of wake generator bars is counted by the trigger signal of each bar on channel 15. To connect the trigger signals another, different BNC signal collector box was used. Beside the hardware modification a new software version was necessary. Already in use on the compressor test facility the possibility to trigger the measurement with a voltage signal has been utilized to control the high frequency data acquisition from the steady-state data acquisition PC. 14 channels are sampled with a sampling rate of up to 60 kHz per sensor. This frequency spectrum is by far sufficient to resolve the flow fluctuations during stall inception as well as the detection of the blade passage frequencies of all stages.

Up to six anemometer bridges operated in the CTA-mode are available for single and dual-sensor hot-wire probes in the DANTEC Streamline anemometer system. Via RS232-interface all adjustments on the Streamline are executed from the data acquisition PC: With the square-wave test the sensors frequency response is tuned and the signal conditioner allows offset-compensation and variable gain for each anemometer bridge output signal to fit this to the AD-board input range. The analog 4-pole Butterworth anti aliasing filter can be set to 3,10 or 30 kHz. The Streamware system uses its own temperature sensor to get the flow temperature at the sensor position.

The Walcher Elektronik Kulite Amplifier system provides six channels with different amplifier gain pre-selections according to the different Kulite sensor types. Each channel is filtered with an analog 8-pole Butterworth anti aliasing filter that can be adjusted in 100 Hz steps up to 50 kHz. Similar to the Streamline system an adjustable output offset and gain allows to utilize the whole AD-board input signal range of ± 5V.

High Frequency Sensor Calibration and Data Evaluation

The six single-sensor hot-wire probes of the sensor array in the compressor inlet (*1.1*) remains uncalibrated. The analysis tools to investigate the stall inception process uses offset-compensated and normalised datasets. Moreover the 5 µm tungsten wires often tear during stall inception because of the high aerodynamic forces occuring in an emerging stall cell. The probe mounts allow the quick change of each destroyed sensor while measuring but calibration would be an unreasonable effort.

The dual-sensor hot-wire probe is calibrated in a free flow calibration unit using the data acquisition system of the compressor test facility. With the traverse unit control the probe angle is selected, the necessary flow data are measured with the steady-state data acquisition and the sensor voltage signals are measured with the high frequency data acquisition. The flow direction angle and the flow speed are varied. The data analysis has to take into account the low pressure in the compressor upstream flow compared to the ambient pressure during calibration. Therefore similar to Poensgen [6] the calibration characteristic is calculated with the mass flow density ρc instead of the flow speed c. The temperature rise in the compressor inlet due to the energy input by the rotating device cannot be neglected in the hot-wire data evaluation. It is calculated from the measured effective power of the rotating disk propulsion.

For the Kulite pressure sensor calibration each probe is calibrated together with its amplifier by pressurizing the probe in a calibration chamber. The Kulite amplifier output voltage is measured together with the calibration pressure. The linearity of the Kulite sensors is satisfying, so that only the gradient of the linear calibration line is determined with a number of calibration points in the measurement range of the sensor. Before a test run on the facility each Kulite amplifier output voltage is adjusted by changing the amplifier offset settings. This is necessary because all sensors are sealed gage type and ambient pressure changes will move the measurement range. An offset measurement as zero balance is then performed with each sensor impinged by the ambient pressure. In the pressure data analysis the correct pressure is calculated with this offset and the gradient from the linear calibration line.

SELECTED MEASUREMENT RESULTS

The experimental results have proved the concept of the coupled steady-unsteady-state data acquisition and the availability of the experimental setup.

The Rotating Inlet Distortion

In order to describe the nature of the rotating inlet distortion, measurements were performed at various compressor speeds and distortion to rotor speed ratios in a stable compressor operating point. The measurement time varied between 5 to 20 seconds in order to make more then 100 inlet distortion periods available for an ensemble averaging of the measurement data. Figure 6 exemplarily displays the total pressure distribution compressor upstream (plane *0*) on the mean flow duct radius at 80% compressor design speed.

With increasing distortion speed the appearance of the total pressure distribution changes from a rectangular to a sinusoidal-like shape combined with a slight decrease in the distortion coefficient $DC_{60°}$ defined as

$$DC_{60^\circ} = \left(\frac{\overline{p_t} - p_{t,60^\circ}}{\overline{q}} \right)_{max} \quad (1)$$

with the annulus averaged dynamic pressure q and total pressure p_t. The relative total pressure loss rises with compressor speed.

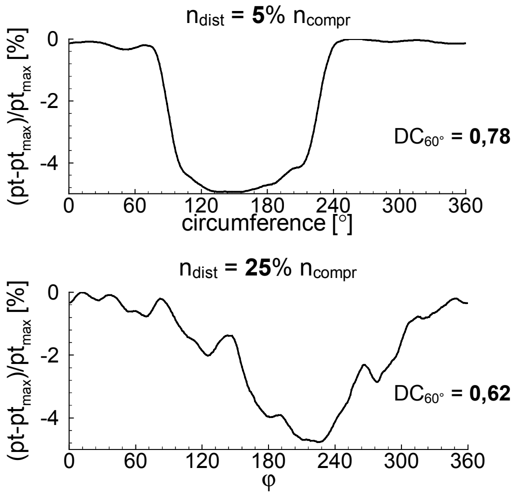

Figure 6: Total pressure distribution at different distortion to rotor speed ratios at 80% compressor design speed

Surge Line Determination

For the investigation of the influence of the rotating inlet distortion on the stable compressor operating behavior it is necessary to determine the surge line at different distortion to rotor speed ratios. For the quality of the experimental results the thermal equilibrium of the compressor is of most importance. Any change in the tip clearance by thermal elongation of the rotor or stator has a strong influence on the surge line. Therefore it is necessary to throttle the compressor close to the surge line and to wait until the operating point in the online monitoring of the compressor map does not move any more for a certain time. Then the throttle is closed in small steps and immediately opened when rotating stall occurs.

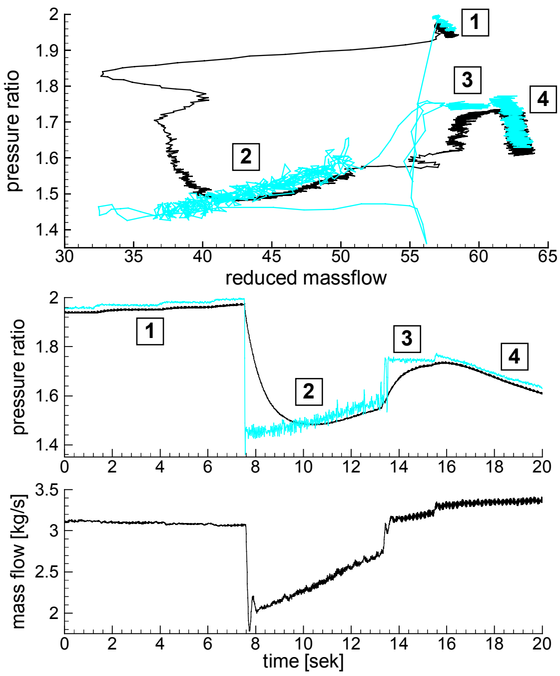

Figure 7: Crossing the surge line at 80 % compressor design speed

The raw time trace of a test run at 80 % compressor design speed and a distortion to rotor speed ratio of 0.25 is displayed in Figure 7. The dark lines represent raw pressure data from the conventional low frequency transducers sampled at 100 Hz. The light lines are processed pressure data from the high frequency total pressure Kulite sensor probes. After low-pass digital filtering with 150 Hz cut-off frequency – far away from the distortion frequency – the average value of one inlet distortion period is used to correspond with one sample of the steady-state data acquisition. For the determination of the pressure ratio the total pressure from the compressor upstream position (plane *0*) is used because the sensor positions in the inlet (plane *1.1*) are occupied by the single-sensor hot-wire array to analyse the stall inception process in the same test run. The reduced massflow in the compressor map

$$\dot{m}_{red} = \dot{m}\frac{\sqrt{T_{t,0}}}{p_{t,0}} \quad \left[\frac{kg}{s}\frac{\sqrt{K}}{bar}\right] \qquad (2)$$

is calculated with $p_{t,0}$ from the Kulite sensor data for the unsteady-state pressure ratio and with the conventional pitot probe data in the same measurement plane for the steady-state pressure ratio. $T_{t,0}$ corresponds to $T_{t,14}$ measured in the settling chamber, the energy input by the rotating inlet distortion generator disk is neglected at such a low distortion speed. With the measured effective power of the distortion disk drive the average total temperature rise can be determined for higher distortion speeds.

The time trace in figure 7 can be divided in four sections: Measurement starts on the compressor speed line [1], the small steps in the pressure ratio vs time diagram reveal the throttle closing procedure. When the compressor stalls a rotating stall cell develops quickly and remains for several seconds [2]. The transients from the stable compressor operation [1] into deep stall [2] in the compressor map only have a qualitative nature because the low-frequency measured massflow change has a delay. Within the rotating stall the steady-state pitot probe in the compressor outlet (*3.5b*) needs a long time to match a representative pressure for the operating point. The unsteady-state pressure ratio is not correctly determined in this case because the pressure data are averaged over the inlet distortion period instead of the stall cell period. When the rotating stall cell collapses a small tip stall [3] remains for about two seconds leaving the compressor on an operating characteristic near the stable speed line. At last the compressor goes back on the speed line [4] revealing the large hysteresis of the rotating stall recovery process.

Effects on the Surge Margin

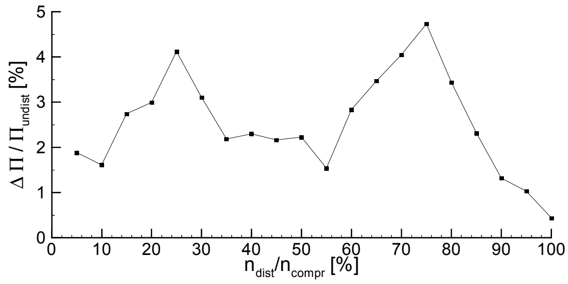

Figure 8: Pressure ratio loss vs distortion to rotor speed ratio at 50% compressor design speed

Figure 8 displays the loss of pressure ratio at the surge line vs distortion to rotor speed ratio for 50 % compressor design speed. Each dot in the graph represents the last stable operating point of a test run as described before. The pressure ratio is determined from the high frequency data evaluation.

A significant loss of surge margin can be found at the 25 % and 75 % distortion to rotor speed ratios. These might represent the eigen-frequencies of the aerodynamic compressor system at the given compressor speed. The results are similar at higher rotor speeds.

Stall Inception

The single-sensor hot-wire probe array in the compressor inlet is used to investigate the stall inception process by analysing the sensor time traces as well as performing the FFT in the time domain and the spatial domain arround the annulus. More advanced methods calculating e.g. the diff. Power Spectral Density (diff.-PSD) of the spatial fourier coefficients and the Travelling Wave Energy (TWE) are available, too. For all of these analysis tools no data from the steady-state data acquisition are necessary. Figure 9 shows exemplarily for the whole compressor speed range the stall inception at 93.3% compressor design speed with a distortion to rotor speed ratio of 0.2.

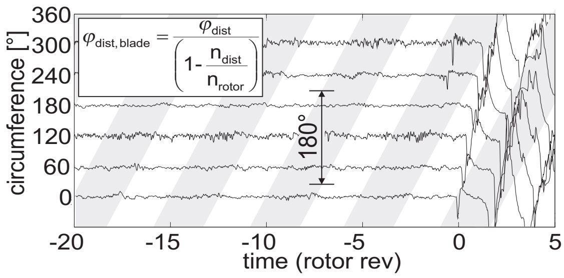

Figure 9: Stall inception at 93.3 % design speed with $n_{dist} = 20\% \, n_{compr}$.

The dataset is digitally filtered with a lowpass filter using a cut-off frequency of 3 kHz and then reduced to a sampling rate of 10 kHz. The time is counted from the stall inception point given in rotor revolutions (rotor rev). Each blade of the rotor remains in the distorted sector for $\varphi_{dist,blade} = 225°$ with a circumferential extension of the inlet distortion $\varphi_{dist} = 180°$ as it is displayed on the time plot where the shaded area indicates the trace of the inlet distortion. Therefore the initial spike starts in the second part of the distorted sector and rapidly grows into rotating stall. The compressor always exhibits rotating stall within one or two rotor revolutions from a spike travelling with about 90% rotor speed. No indications for modal waves can be found in the whole compressor speed range.

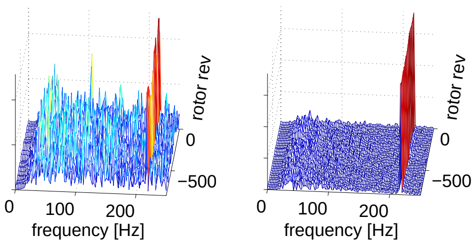

Figure 10: Time FFT of a hot-wire sensor and the Kulite static pressure sensor in the compressor inlet

Figure 10 shows that the FFT of a hot wire sensor signal in the compressor inlet contains a more noisy frequency spectrum compared with the Kulite sensor signal in the same measurement plane. The dataset is measured without inlet distortion, the dominant frequency is the rotor speed frequency at about 220 Hz i.e. 93.3% design speed. Because of the noise level and the insufficient lifetime of the hot-wire sensors it makes sense to replace them by Kulite static pressure taps for the future research project that deals with an active-control setup for the compressor.

Preliminary analysis of the stall inception with rotating inlet distortion shows no change in the spike-type stall inception process. Therefore the significant losses in the surge margin at specific distortion to rotor speed ratios cannot be explained by the type of stall precursor.

SUMMARY

A complete description of the new experimental setup for the investigation of rotating inlet distortions on a 5-stage HP-compressor at the compressor test facility is given. The coupled steady-unsteady-state data acquisition integrates existing data acquisition systems and is presented in detail. The measurement results prove the concept of the data acquisition setup to match the requirements of analysing the effects of an unsteady inlet distortion on the operating behavior and stall inception of the compressor.

ACKNOWLEDGEMENTS

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