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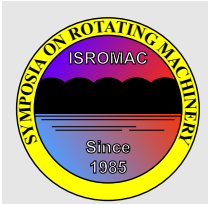
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# Influence of adjusting control accuracy on pressure probe measurements in turbo machines

Tobias W. Zimmermann<sup>1\*</sup>, Oliver Curkovic<sup>1</sup>, Manfred Wirsum<sup>1\*</sup>, Andrew Fowler<sup>2</sup>



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## Abstract

This paper presents a new design of a probe adjusting device intended to position pressure and temperature probes in a flow field. 5-hole, 3-hole and temperature probes can be moved in radial direction and freely rotated about their axis. The high actuation accuracy of  $3.9\mu\text{m}$  in radial direction and  $0.09^\circ$  in angular position is validated in a 2-stage-turbine test rig which is installed at the Institute of Power Plant Technology, Steam and Gas Turbines, RWTH Aachen University. To meet the challenge to calculate the efficiency of a turbo machine which is mainly influenced by the temperature, all probe adjusting devices are positioned simultaneously and controlled by the measuring acquisition system (MAS) so that the same radial position in each stage is measured at the same time. For this purpose a new program has been developed to synchronize actuation and measurement. The slim design of 60mm width allows measurement between the stages of turbomachines with small axial distances between vane and blade. In addition a CFD/FEA shows how the design and combination of materials compensate the thermal expansion of the engine during operation. This allows a minimal safety distance of 0.2mm between rotor and probe to enable measurement as close to the physical boundary as possible. The actuation accuracy is demonstrated with pressure, temperature and angle distribution plots. It is also shown that the resolution of the measuring points, and therefore the actuation distances, has a large impact on the flow field analysis and should be set as high as possible. However the measuring time has to be taken into account

## Keywords

Probe — Measurement — Accuracy

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## INTRODUCTION

Taking the increasing efficiency of steam turbines into consideration, the process parameters need to be enhanced. This thermodynamic enhancement results in a higher density respectively a lower volumetric flow at the inlet of a turbine. For this reason the airfoils, which still need to be developed are indicated by small blade height and low height/chord-ratios. With the usage of shrouded blades the leakage flow losses are reduced [1]. The flow conditions in such flow channels are very complex, thus a CFD simulation without experimental validation is not suitable to optimize the aerodynamic blade design.

For this purpose 5-hole-probes (5HP), 3-hole-probes (3HP) as well as temperature-probes (TP) have to be inserted in the flow channel to determine the radial flow profile across the span. E.g. a 5HP uses five holes arranged as a cross to measure flow angle, Mach number or static pressure calculated by means of pressure differences that can be approximated with calibration matrices gained after calibration in a wind tunnel [2], [3].

All types of probes are positioned with a probe adjusting device (PAD). Modern airfoil designs with tangential end wall contouring (TEWC) impact the flow quite close to hub or tip. To determine any changes within the boundary layer the probe has to be positioned as close as possible to the wall to capture all phenomena.

In addition to a precise linear movement that adjusts the radial

position within a flow channel, the probe design requires rotation of the face perpendicular to the flow due to measurement deviations at the outer boundaries of the calibration area [4]. Therefore the PAD has to ensure a reproducible linear as well as a rotational movement of the probe however the space requirements have to be kept.

The determination of the engine's efficiency is mainly influenced by the temperature difference between inlet and outlet. Smallest deviations of the temperature would cause errors of the calculated efficiency. To ensure that all temperature measurements are simultaneously related to the inlet temperature, it has to be ensured that all probes measure at the same position within the flow channel at the same time.

The present paper therefore shows the results of the measurements at the inter stage of a 2-stage turbine because the most complex flow structure is expected at this location due to rotor-stator interaction and the re-entering of leakage flows. It is shown how the number of measurements across the flow channel influences the measurement quality.

A coarse grid with 13 radial measurements and a fine grid with 56 measurement points are shown in comparison to a CFD prediction. Furthermore the radial adjusting accuracy is evaluated by measuring the same conditions with 3HP and 5HP. The probe heads are different in size respective blockage effect and are calibrated separately with their own calibration coefficients, however the resulting flow distribution has to be

similar. To analyse if the rotational accuracy of the PAD is given, the yaw angle  $\alpha$  is discussed, because it is calculated considering the angle derived by the pressure measurement as well as the physical angle of the probe that is turned at each measurement position towards the flow. In addition 3HP and 5HP are rotated differently to avoid systematic errors.

## NOMENCLATURE

Gr	Grashoff number
L	Characteristical length
Ma	Ma number
Nu	Nusselt number
p	Pressure
Pr	Prandtl number
T	Temperature

### Symbols

$\alpha$	Heat transfer coefficient
$\alpha$	Yaw angle
$\gamma$	Pitch angle
y+	Distance to wall

### Subscripts

10	Plane upstream of the first stage
12	Plane between the two stage
22	Plane downstream of the second stage
in	Inlet
out	Outlet
tot	total
stat	static
w	Wall

### Abbreviations

3HP	3-hole probe
5HP	5-hole probe
ACS	Actuator control software
CFD	Computational fluid dynamics
IP	Internet protocol
FEA	Finite element analysis
GUI	Graphical user interface
MAS	Measuring acquisition system
MP	Measurement plane
OP	Operating Point
PAD	Probe adjusting device
SST	Shear stress transport
TP	Temperature probe
TEWC	Tangential end wall contouring

## 1. DESIGN OF THE PROBE ADJUSTING DEVICE

To meet the introduced challenges of measurements in complex flow fields, a new PAD has been developed. The introduced PAD design allows to move the probe 80mm in radial direction with an accuracy of  $3.9\mu\text{m}$ . Simultaneously, the probe can be rotated around its axis while a precision of  $0.09^\circ$  is realized. To ensure the correct positioning, both parameters are surveyed

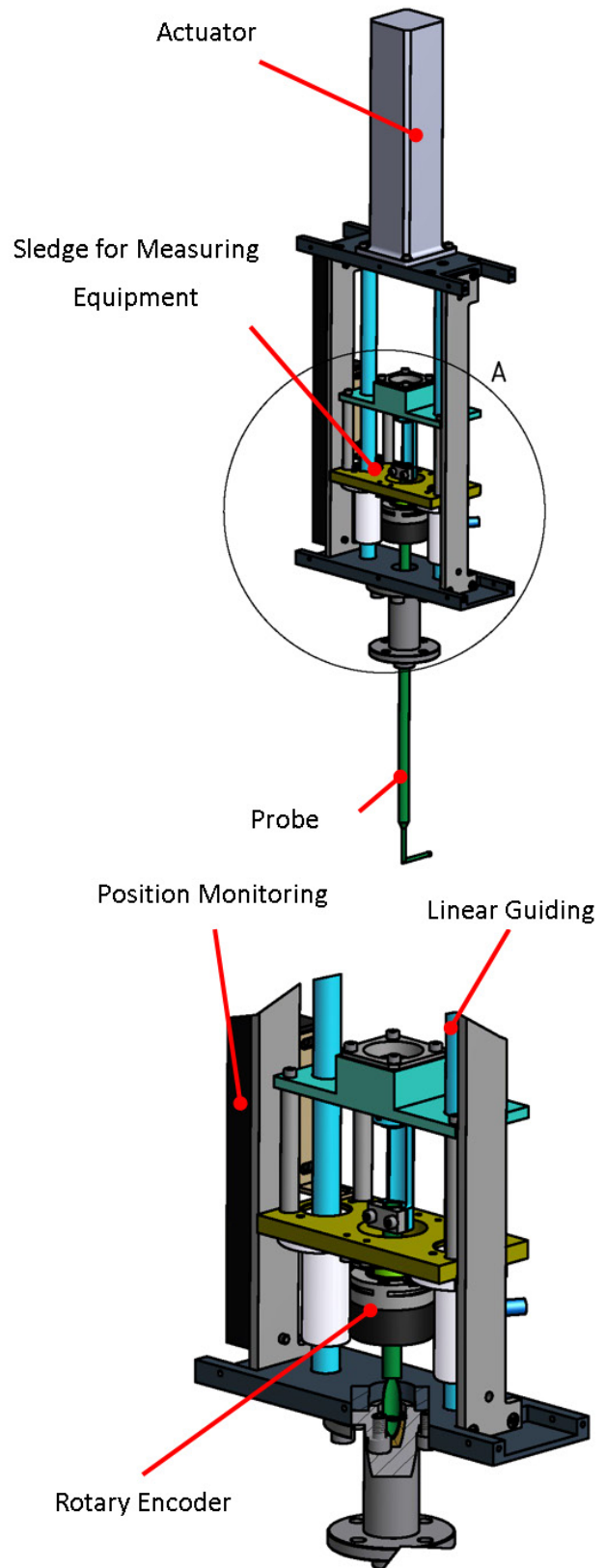


Figure 1. Assembly of probe adjusting device

digitally at the very probe. If the probe is misaligned, the actuator moves until the desired position is reached. The assembled PAD is shown in figure 1. The actuator is placed coaxially to the probe to ensure a slim design of 60mm width. The probe is guided by a sledge that moves along a linear guiding which is designed especially for small tolerances. A connector within the sledge is used to access the pressure tubes or the thermocable of the probes. For the present investigations a 3HP with 1mm height respectively a 5HP and TP with a diameter of about 4mm are used. The position monitoring and the rotary encoder are mounted at the sledge, which ensure to measure the position at the very probe. The sealing of the probe is realised within the adapter flange which also serves to fasten the PAD on the casing of the turbo machine. To ensure the high precision, all components have been manufactured with small tolerances

## 2. ACTUATOR CONTROL SOFTWARE (ACS)

As written in the introduction, the flow in turbo machines is complex and the probe head should face the flow almost perpendicular before the measurement starts. The required simultaneous movement of several PADs has also to be taken into account thus a new program has been developed in LabView®. Figure 2 shows the user interface (GUI) of this new program. Each measurement plane (MP) has its own window which contains two probe monitoring units. The IP of the controller varies for each MP thus the communication protocol is isolated and misguided data packages are outlined. This feature is important to avoid the collision of probe and rotor or casing. Due to the high precision of the PAD, the probes have to be calibrated one time and are then positioned repeatable with a safety distance of about 0.2mm to the hub. A mesh for each probe can be loaded that contains the upper and lower limit of the flow channel and the angle contributed to each radial position within. This ensures a proper measurement of the flow due to a flow facing probe. The current radial position and probe angle is shown in diagrams below the progress bar which displays the status of the current measurement.

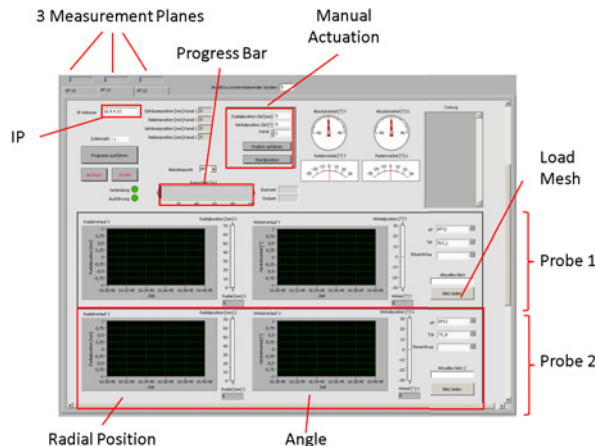


Figure 2. GUI of actuator control software

If necessary, the user may adjust the probe manually. After starting the measurement software for each stage, all probes are moved to the hub. The ACS communicates the status to the MAS that triggers the next probe position after finishing the measurement. This procedure ensures a quick and reproducible monitoring of the flow within the channel.

## 3. TEST RIG SPECIFICATIONS

The test rig is a axial 2-stage test turbine, with shrouded constant section blade design. Tangential end wall contouring is applied on hub and shroud side of the airfoils. Labyrinth seals are used to seal the cavities. Figure 3 illustrates the meridional cross-section of the air turbine schematically. The flow measurement is conducted with a 3HP, 5HP and TP in MP10 (in front of the first stator) and MP12 (inter-stage) and a 5HP and TP in MP22 (behind the second rotor). To measure the flow close to the side walls all probes are positioned with a minimal distance of 0.2mm.

The turbine is supplied with air by two radial compressors at an inlet pressure (static pressure) of  $3.2 \cdot 10^5$  Pa, an inlet temperature (total temperature) of 363.15K and an air mass flow of maximum 14kg/s. The air is pumped in a closed cycle to ensure that changes in environmental conditions do not affect the measurement. The temperature at the compressor and turbine inlet is adjusted by two water driven air coolers. The pressure level in the closed loop is adjusted by a compression load supply and an exhaust valve. The power of the rotor is dissipated using a water brake, mounted in a momentum pendulum with hydrostatic bearings and a maximum performance of 450kW. Via these components the momentum of the rotor can be measured very sensitively by means of a load cell. A honeycomb structure is used at the upstream the first stage to ensure homogenous flow in MP10. The operating points (OP) that are investigated are adjusted by speed while inlet pressure, inlet temperature and pressure ratio are kept constant. OP3 (4775RPM) represents the design point and OP1 (3552RPM) depicts overload conditions. Table 1 summarizes the combined standard uncertainties of flow parameters measured with pneumatic multihole probes

Table 1. Combined standard uncertainties of flow parameters measured with pneumatic multihole probes [6]

Flow parameter	Unit	Uncertainty
$\alpha$	[°]	0.10339
$\gamma$	[°]	0.15626
Ma	[-]	0.0008933
$p_{tot}$	[mbar]	3.1238
$p_{stat}$	[mbar]	3.4108
T	[K]	0.1299

Further details according to the airfoil and sealing setup as well as for the uncertainty analysis can be found in [5] and [6].

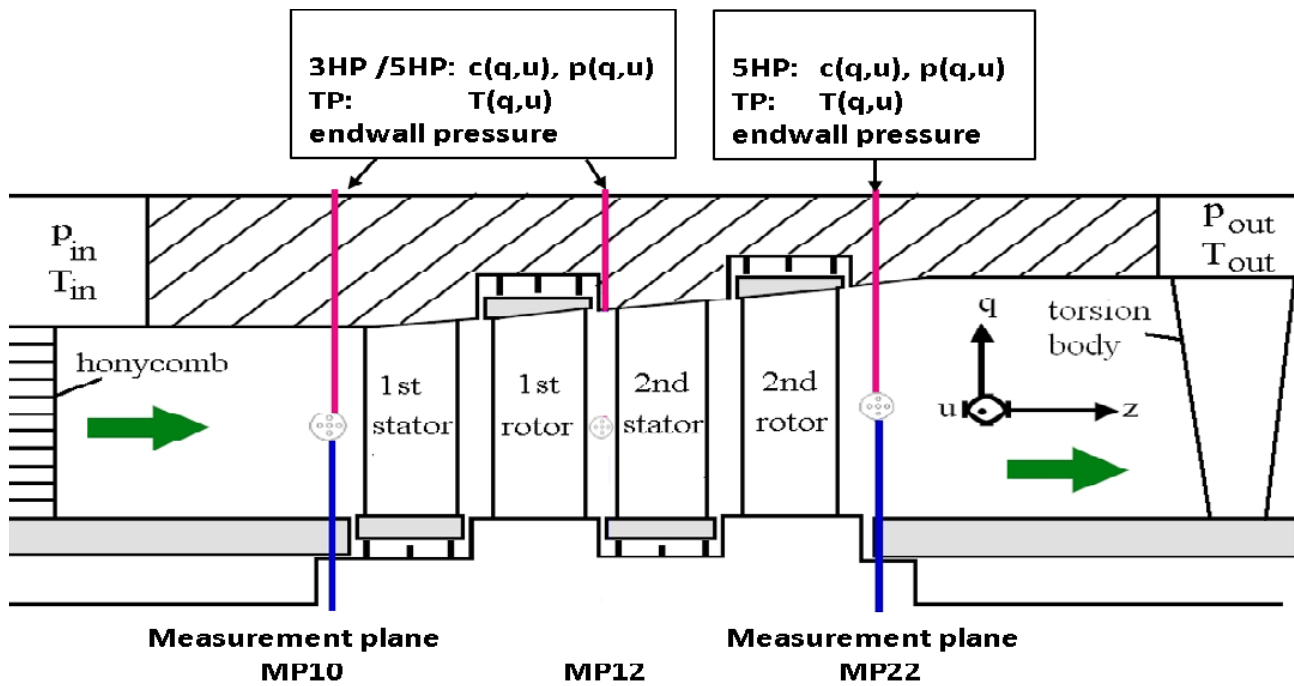


Figure 3. Cross section of the test rig

#### 4. CALCULATION OF THE THERMAL EXPANSION

To ensure that the desired radial position of the probe is not influenced by the thermal expansion of the components due to the heating process, the PAD materials have been chosen carefully. The geometry of the turbine is modelled with the CAD software Autodesk Inventor 2014<sup>®</sup>. The model consists of rotor (green), flow channel (blue), casing (cyan), PAD (magenta) and the probe itself as shown in Figure 4. The highest temperature can be expected at the inlet of the turbine thus the maximal thermal expansion is located in this area, too. Therefore the FEA model does not consider blades or vanes. The meshing was performed with ANSYS ICEM CFD 15<sup>®</sup>. Five nested O-grids cover the contact surfaces of casing, PAD flange and probe (Figure 5). The specific material properties are calculated as shown in Table 2 [7], [8], [9] and

are dedicated to each component. The inlet flow conditions of the test rig ( $Ma=0.15$ ,  $T=363.15K$ ,  $p=3.2 \cdot 10^5 Pa$ ) are used as boundary conditions and an ambient temperature of 298K is set. With this approach, forced convection within the flow channel as well as natural convection on PAD and outer side of the casing are captured.

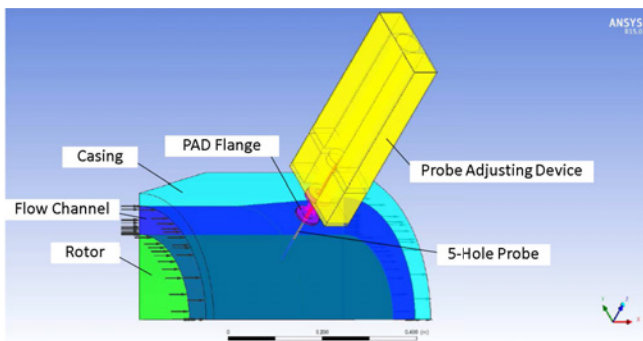


Figure 4. FEA model

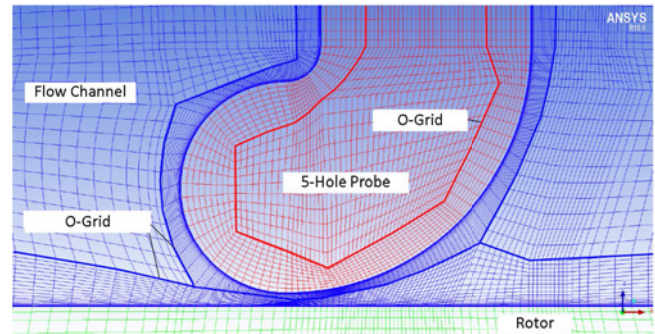
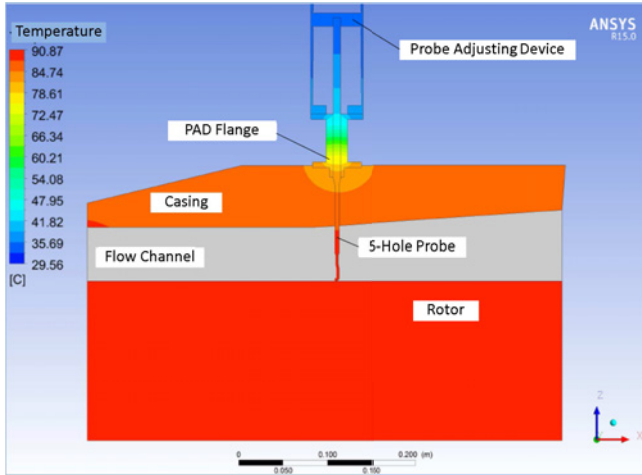


Figure 5. Meshing of probe head and flow channel

A CFD/FEA simulation has been carried out to validate the amount of the probe displacement. Figure 6 shows the temperature distribution within all components after heating up the engine to its operating temperature. It is obvious that the PAD behaves similar to a fin thus the heat is transferred through it more quickly than through the casing. The safety distance of the probe head to the hub is about 0.2mm which is also a significant reason to investigate the thermal expansion due to a collision in case the probe touches the rotor. Table 3 shows the result of the resulting thermal expansion predicted by the simulation:

**Table 2.** Heat transfer coefficients

		Casing	Flange	PAD	Probe
$T_w$	[K]	358.15	323.15	313.15	313.15
L	[m]	0.487	0.06	0.459	0.099
Pr	[-]	0.7075	0.7075	0.7075	0.7075
Gt	[-]	914.24	712.39	19135	1905.6
Nu	[-]	104	14.69	66.82	23.3
$\alpha$	$\left[ \frac{W}{m^2 K} \right]$	5.604	6.425	3.821	6.191


**Figure 6.** Temperature distribution of components

**Table 3.** Thermal expansion of the assembly

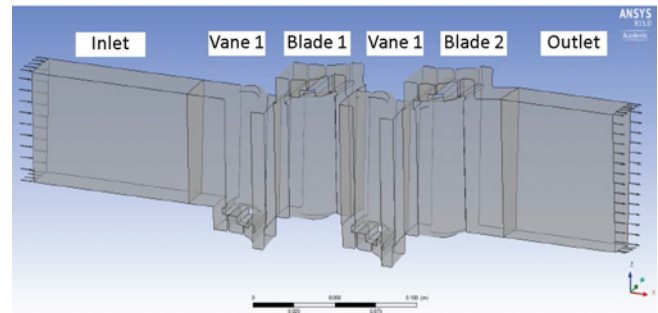
Initial Distance	0.2mm
Rotor	-0.185mm
Casing	+0.290mm
Adapter Flange	+0.031mm
PAD	+0.025mm
Probe	-0.138mm
Resulting Distance	0.223mm

## 5. NUMERICAL SETUP

To analyse the flow, a CFD model of one blade passage has been generated and simulated with the commercial solver ANSYS ICEM CFD 15<sup>®</sup>. Figure 7 shows the flow channel consisting of inlet, outlet and both stages. The simulation area includes labyrinth seals with shrouds and end wall contoured airfoils. The flow channel lies between suction and pressure side of the airfoil to avoid a cut of the end wall contour. The evaluation planes have been set in accordance to the measuring planes in the turbine as described in section 3.

Each blade row consists of 55 airfoils. The numerical model is meshed with ANSYS ICEM<sup>®</sup> by means of a structured H- and O-grid. Due to periodicity of a turbine, only one pitch of

6.54 degree is modeled to reduce the computational effort. A mesh study has been carried out that compares five meshes with 11, 15, 23, 35 and 47 · 10<sup>6</sup> nodes. This study turned out that a mesh with 23 · 10<sup>6</sup> nodes is appropriate to capture all vortices and flow phenomena for the present investigations. The  $y^+$  factor is smaller than 2 and SST is used as turbulence model. It switches between the  $k - \epsilon$ - and  $k - \omega$ -model by means of a blending function to take the advantages of each model depending on the calculated area. Its reliability has been proven in several publications [10], [11] and [12]. For each OP, the boundary conditions are derived by measured 5HP data. At the inlet, the total pressure and total temperature distribution is set. The static pressure distribution serves as outlet boundary conditions for the CFD-simulation. Mixing planes are used to switch the rotating and non-rotating systems.


**Figure 7.** CFD flow channel of the 2-stage turbine

## 6. RESULTS AND DISCUSSION

In advance to the redundant tests that are carried out to verify the accuracy of the new PAD, it has to be checked if the resolution of the measurement is high enough to detect all phenomena that occur within the flow. Especially small vortices which are influenced by the TEWC have to be measured in high resolution to learn how they impact the flow.

Figure 8 shows the total pressure distribution of the channel in measurement plane MP12 that is located between the two stages of the turbine. This MP has been chosen for all further investigations because the interaction of rotor and stator cause the most complex flow structure effects. Two different resolutions of the PAD grid are compared to the CFD simulation. The coarse grid with 13 radial measurements that was measured in a previous investigation (same experimental setup) with another probe adjusting device is plotted in blue. The curve in red shows the measurement data with the new PAD and a higher resolution of 56 steps. The span height is the same for both grids. OP1 has been chosen because it represents overload condition and therefore shows more turbulence compared to OP3.

Please note that the CFD simulation serves to illustrate the vortex phenomena. However one can see that the CFD prediction shows deviations compared to the test, its quality is sufficient to depict the present flow structure.

The reader may recognise a more detailed distribution of the vortices at 30% and 83% radial height for the fine mesh

compared to the coarse mesh. The chosen resolution impacts the flow angle measurement even more than the pressure measurement which is shown in Figure 9. It is obvious that the missing measurement points at 20% radial height do not cover the angle distribution correctly. At this position the flow shows an angle of  $-40^\circ$  instead of  $-35^\circ$ . Actually a higher deflection is predicted by the CFD which leads to the assumption that the test with low resolution does not detect the flow properly. This result supports the statement that a suitable resolution is as important as the precise positioning to detect all effects within a complex flow field. With this knowledge the resolution for all further tests has been set to 56 steps per radial height.

To validate the positioning accuracy of the new PAD several tests have been performed with the introduced test rig. Two operating points (OP1 and OP3) have been measured two times on several days to ensure that the distribution curves are not influenced by the probe type itself, the measurement has been conducted with a 3HP first and then has been repeated with a 5HP. Two different TP were inserted respectively however the design has been the same.

The measured data shown in Figure 10 - Figure 12 is compared to the CFD results. It has to be taken into account that the data of the 5HP measurement has been used as boundary condition for the CFD simulation, which is plotted in each diagram because the focus lies on the position of flow phenomena especially close to the hub and tip side where the main impact of the TEWC is expected.

Figure 10 shows the total pressure distribution in MP12. The vortex peaks at 16%, 31% and 83% for OP1 as well as the peaks at 9%, 22% and 88% radial height for OP3 are measured redundantly on both test days. Positions and magnitudes of the peaks are also predicted by the CFD. For OP1 both measurements also show the same distribution. However the CFD matches the experimental data in the center of the flow channel, deviations occur on the casing side. For both OP it has to be mentioned that the CFD predicts peak amplitudes close to the hub which are not measured in the experiment.

The temperature peaks at 20%, 33% and 86% for OP1 and 12%, 30% and 82% radial height for OP3 shown in Figure 11 have been measured reproducibly as well. deviations between both measurement days are below 0.1K. Due to the small changes in efficiency that are investigated nowadays, such amount of deviation has to be ensured to answer questions of efficiency improvements related to new features. Therefore the measurement of all probes in all MP is triggered at the same time and the same span position respectively.

The yaw angle has also been taken into consideration because the actuation accuracy around the axis impacts its calculation immediately. It is calculated by summation of the physical probe angle that is set with the PAD and the derived angle which results of the probe pressure measurements. Therefore the probe adjusting accuracy impact the yaw angle directly. One can see that the channel vortex which is located between 10% and 40% radial height causes a massive deflection of the flow in both directions. This deflection requires rotation of the probe towards the flow due to the fact that 3HP and 5HP

only work probably up to an angle of approx.  $\pm 25^\circ$ .

Ideally, the probe faces the flow perpendicularly before the measurement is triggered. Therefore a CFD simulation is run before the test and the predicted distribution is used to program the adjusting mesh for each OP. The calculation of the flow angle by pressure differences can be observed online during the test. This measure allows to survey if the adjusting mesh has been set correctly. In case that an angle range of  $10^\circ$  is exceeded, the meshed can be modified to increase the measurement accuracy.

The curves in Figure 12 clarify that even changes of about  $40^\circ$  (OP1 20% - 30% radial height) can be measured properly and repeatable due to tracking the probe almost perpendicular to the flow at each measuring position. In addition, the radial actuation accuracy has been verified because the head diameter of the 3HP is different to the 5HP design which would result in a radial offset if the PAD would not adjust the probes properly.

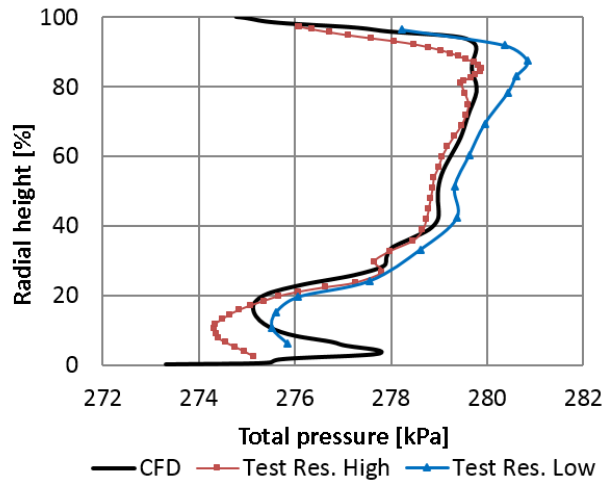


Figure 8. Total pressure in measurement plane 12

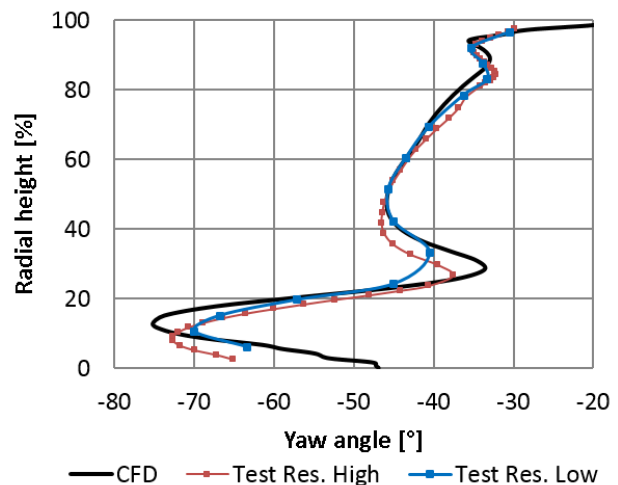


Figure 9. Yaw angle in measurement plane 12

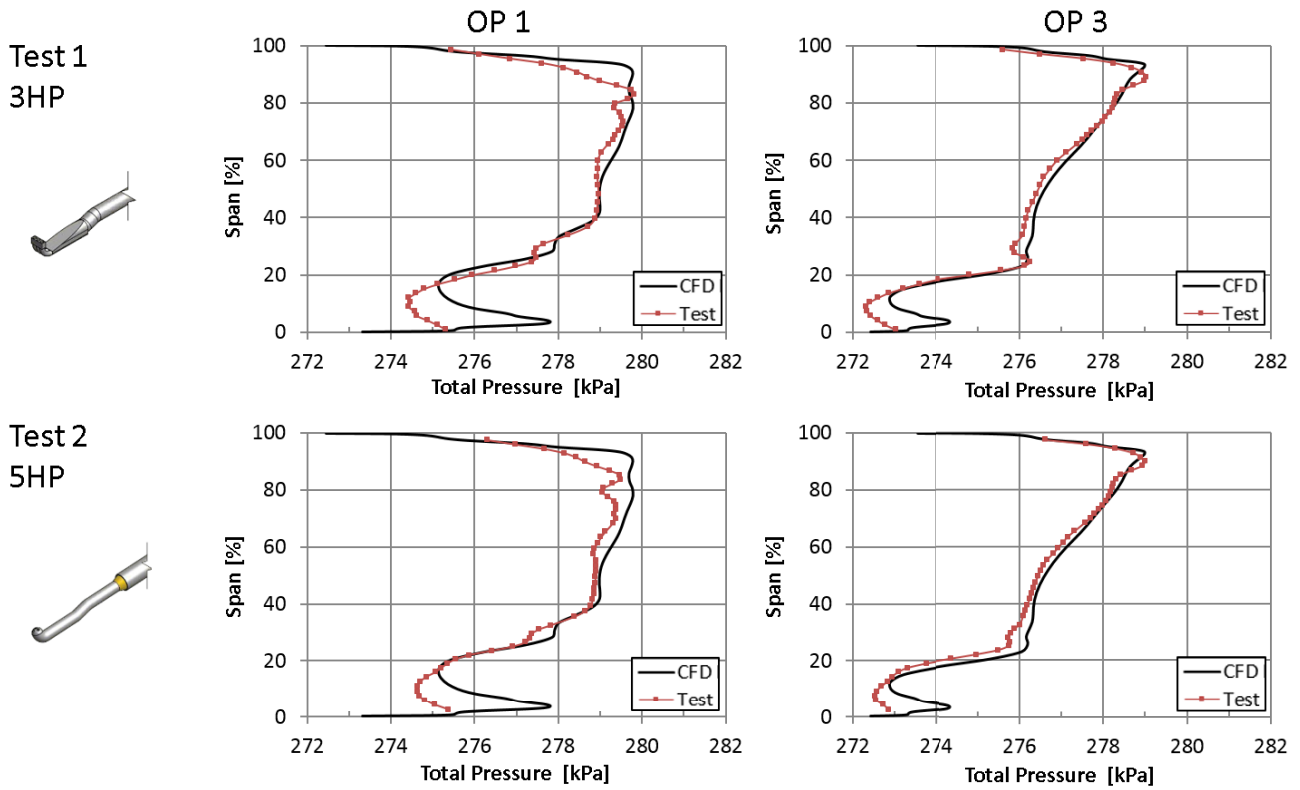


Figure 10. Total pressure distribution in measurement plane 12 for two operating points

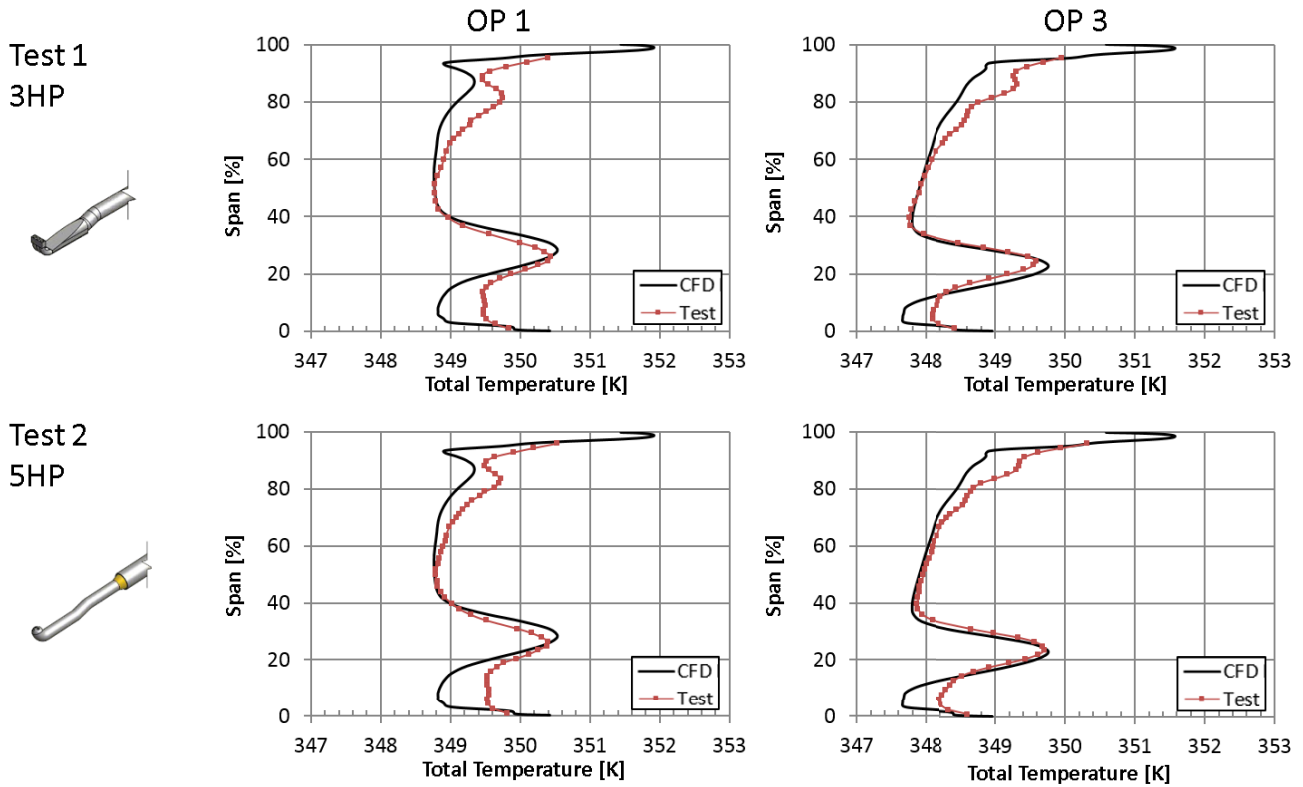
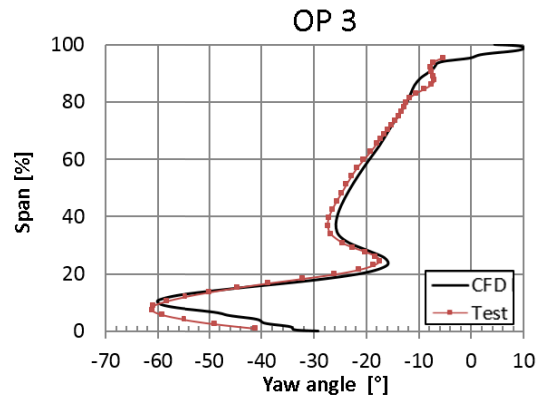
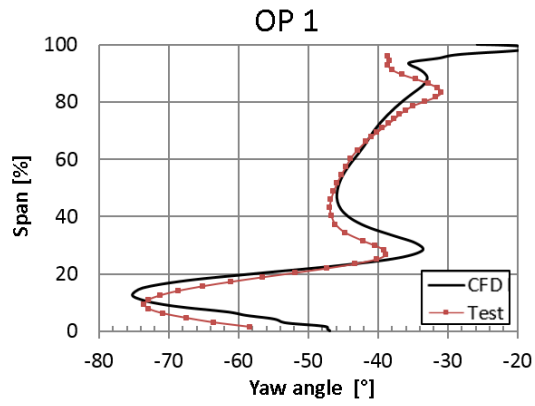
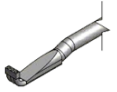


Figure 11. Total temperature distribution in measurement plane 12 for two operating points



Test 1  
3HP



Test 2  
5HP

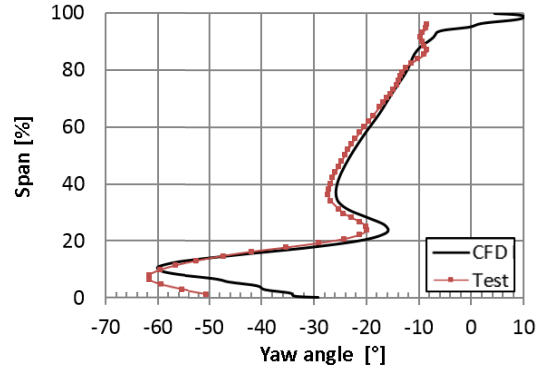
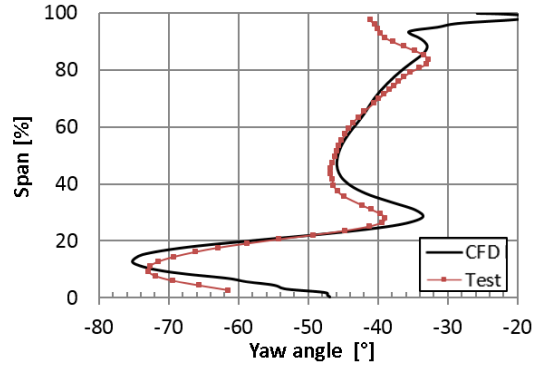
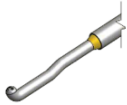


Figure 12. Yaw angle distribution in measurement plane 12 for two operating points

## 7. CONCLUSION

Complex flow phenomena in turbo machines require highly resolved measurements within the flow channel to validate numerical simulations and to learn specific details of vortex systems. Probes have to be positioned precisely and redundantly within the annulus to provide this data. Limited installation space of many applications demand compact units to fulfil this purpose. For that reason a new probe adjusting device has been developed at the Institute of Power Plant Technology, Steam and Gas Turbines, RWTH Aachen University that is able to move 3HP, 5HP and TP to a desired position. The small width of 60mm and the high actuation accuracy of 3.9µm in radial direction and 0.09° around the probe's axis characterize this new design.

The material combination of all parts has been chosen with respect not to impact the radial probe position neither to allow a collision of probe and rotor. A FEA/CFD as well as measurements on a 2-stage turbine test rig have demonstrated that an initial distance of 0.2mm probe to hub at ambient conditions changes only by about 0.023mm after heating up the engine to its operating temperature of 363.15K.

Even smallest deviations of the inlet temperature could cause errors of the efficiency measurement if other temperature measurements cannot be related to it. For this purpose a new software application has been programmed which allows to move several probes time synchronized to measure e.g. the temperature in each stage simultaneously. This enhances the accuracy of efficiency determination strongly because the temperature drop over stages or the complete engine is measured at the same time.

To ensure that the probe measures accurate, a mesh can be loaded for each probe. It contains the boundary positions on the casing and hub side as well as the contributed angles for each radial position that have been determined via CFD in advance. This procedure allows to rotate the probe almost perpendicular to the flow at each measuring position for a specified OP.

Two operating points were measured on different test days with different kind of probes redundantly. The results show that the probe adjusting device actuates the probes as precisely as demanded. CFD simulations have been carried for both OP to allow comparison of the redundant test days. These results show likewise that the position accuracy of the new PAD meets all requirements to survey complex flows in turbo machines

## ACKNOWLEDGMENTS

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