CALIBRATION AND IMPLEMENTATION OF A TRANSIENT SUB MINIATURE 5-HOLE PROBE TO DETERMINE COMPLEX FLOW STRUCTURES IN TURBOMACHINES

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ABSTRACT

Pneumatic multi-hole probe measurement is a common approach to determine flow phenomena in turbo machines. Therefore e.g. 3-hole-probes and 5-hole-probes are positioned on several radial positions within the flow channel which allows to measure flow characteristics such as pressure as well as Mach number and flow angle. The most common measurement technique is steady state because the pressure sensors have to be installed outside to the flow channel and small pressure fluctuations would be averaged between the probe head and the sensor. Nowadays the increasing computational power allows to run complex transient CFD simulations which answer questions of wake distribution and other transient flow phenomena. Therefore it is necessary to validate these numerical results experimentally. For this purpose, several probes designs with embedded sensors have been published. Kulite developed a spherical 5-hole-probe head (FAP-250) with integrated transient sensors that are located at the very bore position what allows to perform such experimental investigations. This probe head was added to a stem and integrated into an existing probe adjusting device to determine the full radial flow distribution. Measurements are conducted at the outlet of the second stage of a 2-stage axial turbine located at the Institute of Power Plant Technology, Steam and Gas Turbines, RWTH Aachen University. The results are validated against steady state data measured via 5-hole probe using the same blade configuration. The paper answers questions about calibration and post processing. Finally, the wake distribution of different operating points respectively blade loadings is visualized and discussed.

NOMENCLATURE

f_S	Sampling rate of MAS
h	Damping factor
K	Calibration factor
Ma	Mach number
p	Pressure
r	Radius related to machine axis
s	Displacem. of probe due to rotation

Symbols

α	Yaw angle
γ	Pitch angle
Δf	Sampling rate
Δ_A	Amplitude deviation caused by probe response
Δ_φ	Phase deviation caused by probe response
δ	Angle caused by traversing probe
ϑ	Rotational angle of the probe
φ	Phase
φ	Angle between casing joint and probe
ϕ	Corrected angle of probe head
ω	Frequency
ω_0	Natural frequency
$\otimes$	Correlation

Subscripts

1	First stage
2	Second stage
10	Plane upstream of the first stage
12	Plane between the two stage
22	Plane downstream of the sec. stage
Stat	Static
Tot	Total

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Abbreviations

3HP	3-hole probe
5HP	5-hole probe
AC	Autocorrelation
CC	Cross-correlation
CFD	Computational fluid dynamics
FFT	Fast Fourier transformation
IST	Institute of Jet Propulsion and.Turbomachinery
MAS	Measuring acquisition system
MP	Measurement plane
OP	Operating point
PAD	Probe adjusting device
PT	Periodic time
R	Rotor
RF	Repetition frequency
RPM	Revolutions per minute
S	Stator
TP	Temperature Probe

INTRODUCTION

Due to the quick increase of global energy consumption and political as well as social restrictions, the efficiency of turbo machines is placed in the focus of society. The development and optimization of turbo machines, which are used for common power conversion as well as for aviation, requires experimental tests to validate theoretical considerations and numerical simulations. Therefore, the conditions of flow have to be determined very precisely at various positions and operating points within the flow channel. For this matter probes are inserted through the casing and positioned within the flow. This allows to determine the flow field in terms of pressure distribution, temperature, velocity and direction at a discrete point within the duct. Due to the complex three dimensional and unsteady flow between the stages of a turbo machine, transient measurement is an essential tool to understand the occurring flow phenomena and to finally improve the engines efficiency

5-hole-probes (5HP) are established to observe three dimensional flow. The pressure is measured at each hole simultaneously. If the flow is not perpendicular to the probe's head (see Figure 1), pressure deviations occur that can be transferred to flow parameters such as total pressure, static pressure, Mach number, or flow angle using characteristic diagrams which have been generated in advance in a wind tunnel. Due to space requirements and the claim to impact the flow as less as possible, the probe is usually designed very small to measure within turbo machines. For this reason the probe consist of probe head and shaft with integrated capillaries that are connected to each pressure hole. These capillaries are connected with tubes to the pressure sensor in common measurement setups. The distance between hole and sensor does not allow to measure transient fluctuations due to the damping effect of the fluid within the tube [3].

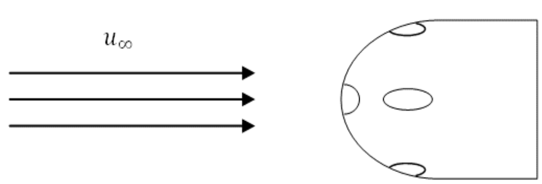

Figure 1: Incidence of 5HP

To avoid this pressure damping effects within the capillaries, several designs of probes with embedded sensors have been proposed in the past. In 1973 Senoo et al [1] used a 5HP with transducers embedded within the shaft however there is still a distances to the measurement point. Kerrebrock et al.[2] started to pursue the strategy to implement the sensors close to the surface and presented a 5HP with spherical head in 1980. A comprehensive overview of early probe designs and measurement techniques for transient flows is given by Ainsworth et al.in [3], Kupferschmied et. al [4] and Sieverding et al. [5]. Dell'era et al.[6] showed results measured with a single sensor fast response probe used as a theoretical 3-hole probe (3HP). The FRAP probe has been developed at ETH Zürich and results were e.g. presented by Regina [7].

Time resolved pressure measurement is quite sensitive to several disturbances which have to be taken into account in an uncertainty analysis. Treiber et al. [8] point the way to applicate such an analysis to steady state pneumatic probes. Dell'era et al. [6],[9] extended these investigations to transient pressure measurements by using the ASME standard methodology.

EXPERIMENTAL SET UP

The measurements are performed on the 2 stage axial turbine test rig of the Institute of Power Plant Technology, Steam and Gas Turbines, RWTH Aachen University. The air is supplied by two radial compressor which operate in closed loop cycle to ensure independency of environmental changes. The compressors have got a nominal power of 1.8MW and are able to provide a mass flow rate up to 13.9kg/s. Four operating points (OP) are investigated. These are adjusted by means of a water-break respectively speed while thermodynamic boundary conditions (inlet pressure, inlet temperature and outlet pressure) are kept constant. The air reaches the first stage with Ma = 0.15 at 3.2bar and 90°C and is expanded to 2.31bar. The speed varies between 3500RPM and 5200RPM. An incremental rotary encoder is used to assign measurements to phase and to ensure correct ensemble averaging. The three dimensional airfoils are shrouded and sealed with labyrinth seals on the hub side and a

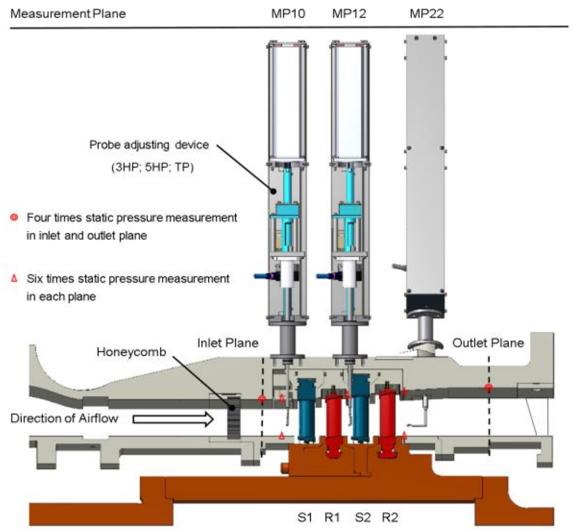

Figure 2: Cross section of the 2 stage axial turbine

combination of labyrinth and brush seal at the casing side. Figure 2 shows the cross section of the test rig.

The commercial spherical 5HP head (Kulite FAP-250) has been implemented to a stem and is adjusted by the high precision probe adjusting device developed by Zimmermann with an accuracy of about 3.9µm and 0.09° (further details are published by Zimmermann et al. [11]). Its diameter of about 8mm is twice as large as the common steady 5HP used in this test rig thus it has to be accepted that flow phenomena cannot be detected as close to the wall. Also the different blockage effect of the probe and its related influence to the flow has to be considered. Both probes are shown in Figure 3. To reduce the interaction of the stem to the measurement, the probe head is mounted on a cranked support, however this design impacts the post processing of the measurement which is explained later. Technical specifications of the FAP-250 probe head are given by Ned et al. [12] and are therefore not further considered in this paper.

Figure 3: a) Transient 5HP, b) Steady state 5HP

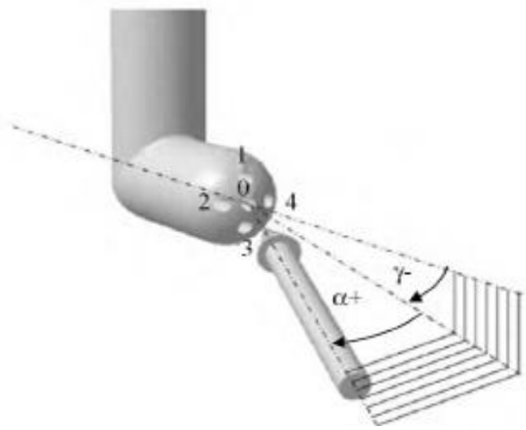

Figure 4: Definition of 5HP hole-numbering, yaw and pitch angle

WINDTUNNEL CALIBRATION

The static calibration of each sensor including temperature compensation [4], [12] has been conducted by Kulite. After manufacturing and set up of the measurement acquisition system (MAS) the probe has been calibrated in the open jet wind tunnel of IST at RWTH Aachen University.

An angular range for yaw and pitch from -20° to 20° was calibrated for three Ma numbers (0.1, 0.15 and 0.2). in accordance to the steady state calibration that have been proven to be accurate [11]. In a wind tunnel the Ma number as well as the incidence of the probe is known and the so called K factors can be calculated with the following equations according to Bohn et al [13]. Figure 4 shows how the bores of the 5HP are numbered and which angle definition is used. After calibration it is possible to derive flow conditions by means of pressure differences in an unknown flow field using multiple parameter approximation.

$$K_\alpha = \frac{p_2 - p_4}{\Delta p} \quad (1)$$

$$K_\gamma = \frac{p_1 - p_3}{\Delta p} \quad (2)$$

$$K_{Mach} = \frac{\Delta p}{p_0} \quad (3)$$

$$K_{stat} = \frac{p_{stat} - p_0}{\Delta p} \quad (4)$$

$$K_{tot} = \frac{p_{tot} - p_0}{\Delta p} \quad (5)$$

$$\Delta p = p_0 - \frac{p_2 + p_4}{2} \quad (6)$$

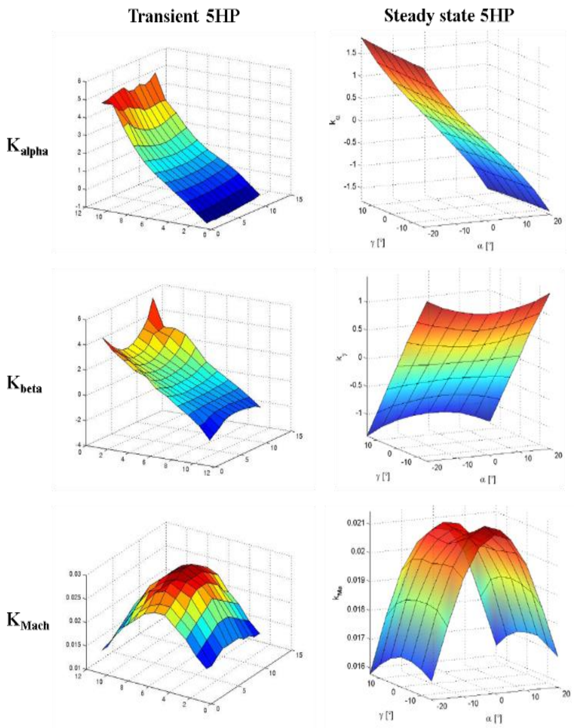

Figure 5: Calibration results for angles and Ma number, transient probe on the left vs. steady state probe on the right

DYNAMIC CALIBRATION

If a measurement is conducted in an environment with high periodic oscillations one can assume that the measuring device influences the signal with its damping resonance if a certain frequency is passed. This results in a discrepancy of amplitude and a shift in phase caused by vibration response of the sensor itself. Therefore the Eigen-frequency has to be significantly higher than the frequency of the measured signal to minimize an error caused by an inaccurate sampling rate.

A typical repetition rate in turbo machinery lies between 2 to 15kHz [14][15]. The four operating points (OP) of the present turbine show repetition frequencies (RF) of 3.26kHz up to 4.73kHz. In addition fluctuating parts resulting of turbulence and acoustics cause frequencies of about 40kHz that have to be taken into account. The natural frequency of the FAP-250 probe head is 300kHz and Kulite states that a flat response of 100kHz can be expected which indicates that further dynamic calibration is not required. Several publications have been found that verify this statement [15]-[19].

To calculate the percentage deviations in amplitude or phase, equations (10) and (11) are evaluated. The damping factor h is provided by Kulite.

$$F(j\omega) = \frac{1-\left(\frac{\omega}{\omega_0}\right)^2 - 2\cdot j\cdot h\cdot\left(\frac{\omega}{\omega_0}\right)^2}{\left(1-\left(\frac{\omega}{\omega_0}\right)^2\right)^2 + 4\cdot h^2\cdot\left(\frac{\omega}{\omega_0}\right)^2} \tag{7}$$

$$|F(\omega)| = \sqrt{\mathrm{Re}\big(F(j\omega)\big)^2 + \mathrm{Im}\big(F(j\omega)\big)^2} \tag{8}$$

$$\varphi = \arctan\left(\frac{\mathrm{Im}(F)}{\mathrm{Re}(F)}\right) \tag{9}$$

$$\Delta_A = \frac{|F(\omega)|-1}{1}\cdot 100\% \tag{10}$$

$$\Delta_\varphi = \frac{\varphi}{360°}\cdot 100\% \tag{11}$$

Table 1summarises the deviations for all OP of the turbine. It is obvious to see that these deviations can be neglected for the present test case as stated by the supplier.

Table 1: Percentage deviation of probe response

OP	ω_0[kHz]	Δ_A[%]	Δ_φ[%]
1	3.26	0.0118	0.000127
2	3.86	0.0165	0.000150
3	4.38	0.0213	0.000170
4	4.73	0.0248	0.000184

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POST PROCESSING

In addition to a successful measurement the post processing of data is another key factor to ensure high quality results. It has been shown that the aerodynamic calibration of the transient probe lies in good accordance to the steady state calibration curves that are given in Figure 5. In a next step these calibration matrices have to be adopted on the measured pressure values to derive the turbine’s flow characteristics. The probe gathers data on 56 discrete positions to detect the flow field over span. This requires that each measurement is related to the same trailing edge of an airfoil. Therefore, one “master airfoil” has been marked in advance and the count position of the incremental rotary encoder was stored for a horizontal alignment to the casing joint as shown in Figure 6. The mounting angle φ of the transient 5HP has to be considered to link the probe and airfoil position.

Due to the cranked design of the stem, two further displacements occur that have to be considered. As shown in Figure 7 an angle deviation δ is caused just by traversing the probe from hub to tip. To ensure that the probe is working in its calibrated angular range, it has to be rotated toward the flow. The flow direction for each radial position has been predicted by CFD in

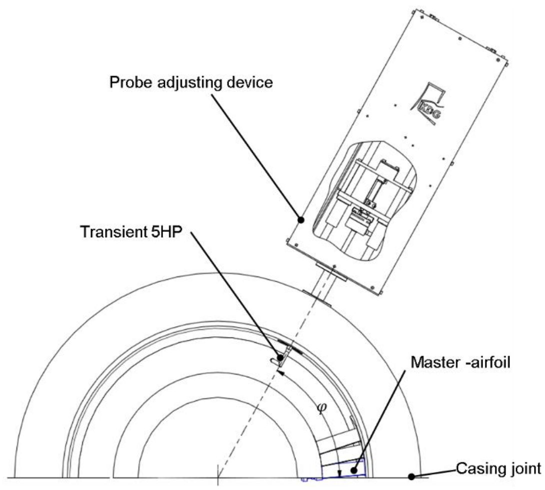

Figure 6: Zero count definition of master airfoil

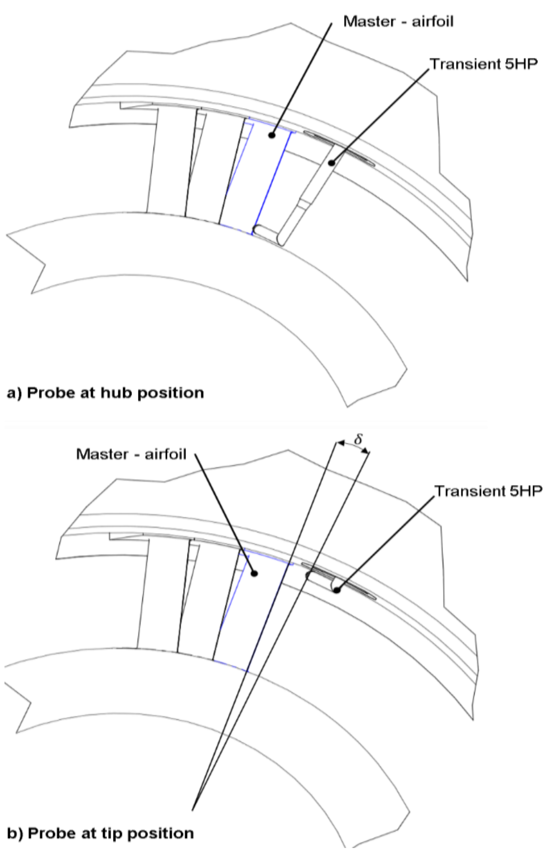

Figure 7: Change of distance between probe head and trailing edge due to cranked stem. a) Probe at hub position b) Probe at tip position

advance and thus each radial position is linked to a specified angle. This rotation of the probe by an angle ϑ causes the displacement s that is shown in Figure 8. Equation (12) considers these changes of the probe position using the length of the crank and the radial probe position related to the machine axis.

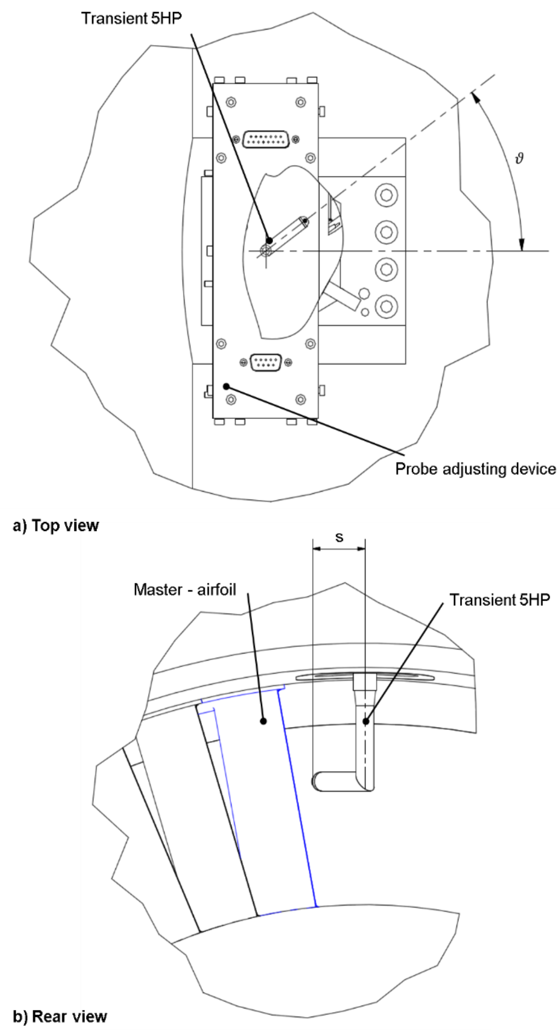

Figure 8: Displacement s caused by rotation of the probe. a) Top view and rotating angle ϑ b) Rear view and displacement s

$$\phi = \varphi + \delta + \tan^{-1}\left(\frac{s}{r_{\mathrm{Probe}}}\right) \tag{12}$$

$$s = l_{\mathrm{crank}} \cdot \sin(\vartheta) \tag{13}$$

In a first step, the post processing software splits the raw data. A vector is generated for each circumferential position of the rotor derived by the raw count of the rotary encoder at each radial measuring positon. By applying equation (12), the corrected rotor angle ϕ, where trailing edge and probe head are aligned, is known. After calculation of the correct rotor position several methods are applied to check whether the number of recorded revolutions is appropriate and if the measurement is consistent.

Fast Fourier Transformation [20]

Fast Fourier transformation (FFT) can be used to perform a spectral analysis of a time discrete signal. The result answers questions of occurring frequencies within the signal which is investigated with a certain sampling rate Δf as shown in equation (14). N represents the number of data elements and f_S is the sampling rate of the MAS. The discrete FFT is carried out using equation (15)

$$\Delta f = \frac{f_S}{N} \tag{14}$$

$$X_S(w) = \int_{-\infty}^{+\infty} x(t) \cdot e^{-i\omega t} dt = \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{i\,2\pi\,k\,n}{N}} \tag{15}$$

with n= 0,1,…(N-1)

Figure 9 shows the result of a FFT for the centered bore p_0 sampled at 100kHz in OP4. One can clearly identify a major peak at ≈4,7kHz which matches the calculated natural frequency of 4,73kHz of OP4 as shown in Table 1. Furthermore a broad spectrum of frequencies lies below this peak.

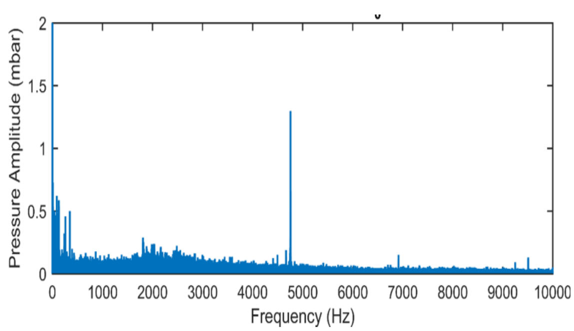

Figure 9: FFT Analysis for center pressure hole p_0 and OP4 measured with 100kHz

Auto correlation [21]

Correlation is a measure to check the match of two signals. Utilizing autocorrelation (AC) the same signal is compared to itself. Equation (16) gives the definition of an auto correlated function x(t).

$$R_{xx}(t) = x(t) \otimes x(t) = \int_{-\infty}^{+\infty} x(t) \cdot x(t+\tau) d\tau \tag{16}$$

and

$$R_{xx} = Y_j = \sum_{k=0}^{N-1} x(\tau)_k \cdot x_{j+k} \tag{17}$$
$$j = -(N-1), -(N-2), \ldots, (N-2), (N-1)$$

A normalized autocorrelation (equation (18)) is used to analyze the transient pressure data.

$$\overline{R_{xx}}(\tau) = \frac{R_{xx}(\tau)}{R_{xx}(\tau = 0)} \leq 1 \tag{18}$$

Figure 10 shows the results of the auto correlation for all probe pressures taken OP4 as example.

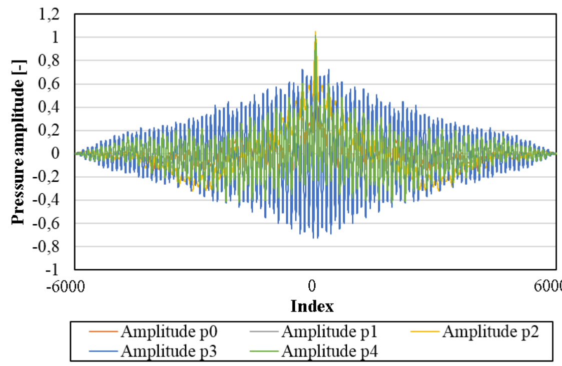

Figure 10: Auto correlation of all probe pressures for OP4

Cross correlation [20]

In addition to autocorrelation, the data is also cross correlated (CC) which means that the signal is not compared to itself then to another one and investigated concerning similarities. The cross correlation $R_{xy}(t)$ of signal x(t) and y(t) is defined by equation (19)

$$R_{xy}(t) = x(t) \otimes y(t) = \int_{-\infty}^{+\infty} x(t) \cdot y(t+\tau) d\tau \tag{19}$$

$$x_j = 0, j < 0 \text{ or } j \geq N \text{ and } y_j = 0, j < 0 \text{ or } j \geq M$$

and

$$R_{xy} = h_j = \sum_{k=0}^{N-1} x(\tau)_k \cdot y_{j+k} \tag{20}$$
$$j = -(N-1), -(N-2), \ldots, -1, 0, 1, \ldots (M-2), (M-1)$$

The normalized form is also used for cross correlation and may be calculated with equation (21).

Both types of correlations are used to check if the transient measurement of the independent sensors within the probe head is working properly. The RF and respectively the periodic time (PT) is known for each OP thus AC has to show a maximum for all multiples of the PT. CC is applied to adjoining sensors of the probe and maxima should appear at multiples of 50% PT.

Having a look on the resulting correlations shown in Figure 10 and Figure 11 it is obvious too see that the correlation (blue) has its maximum in the center and decreases monotonically to both sides which indicates that the different pressure sensors measure correctly.

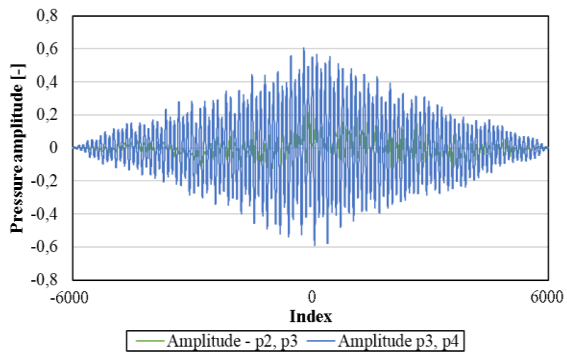

Figure 11: Cross correlation of probe pressures p_2 vs. p_3 and p_3 vs. p_4 measured with 100kHz

DISCUSSION OF MEASUREMENT RESULTS

The previous section has shown that the quality of the measured data is appropriate and how the data has to be treated to compensate errors that occur due to the probe positioning. Figure 12 shows the distribution of one bore pressure for all 56 radial measuring positions over time to understand the impact of the corrections that are conducted in the post processing. The wake that is caused by the passing airfoil can be clearly seen as valley marked in red color. By correcting the start time for each radial position to the related moment where the master airfoil passes the probe, each data row is shifted. This causes a smoother distribution of the wake shape. All further shown data is sampled with 100kHz and ensemble averaged. The time scale is equal for each diagram starting with the passing master airfoil.

For purpose of validating the transient pressure data against the stationary 5HP measurement, the static pressure is circumferentially averaged. It is shown in Figure 13 that the transient measurement matches the stationary distribution quite well in the overall level however, deviations can be seen especially in the hub region that could be caused by the larger probe head diameter of the transient 5HP. However it has to be noticed that these deviations are smaller than 1%.

By comparing all four operating points one can observe several major changes in flow for part- and over load compared to the design point OP3. Figure 14 illustrates a three dimensional distribution of the pressure distribution across the span. It is remarkable to observe how the pressure level changes decrease by comparing OP1 to OP3. A top view shown in Figure 15 clarifies how the wake propagates through the flow channel and shows the changes of the occurring

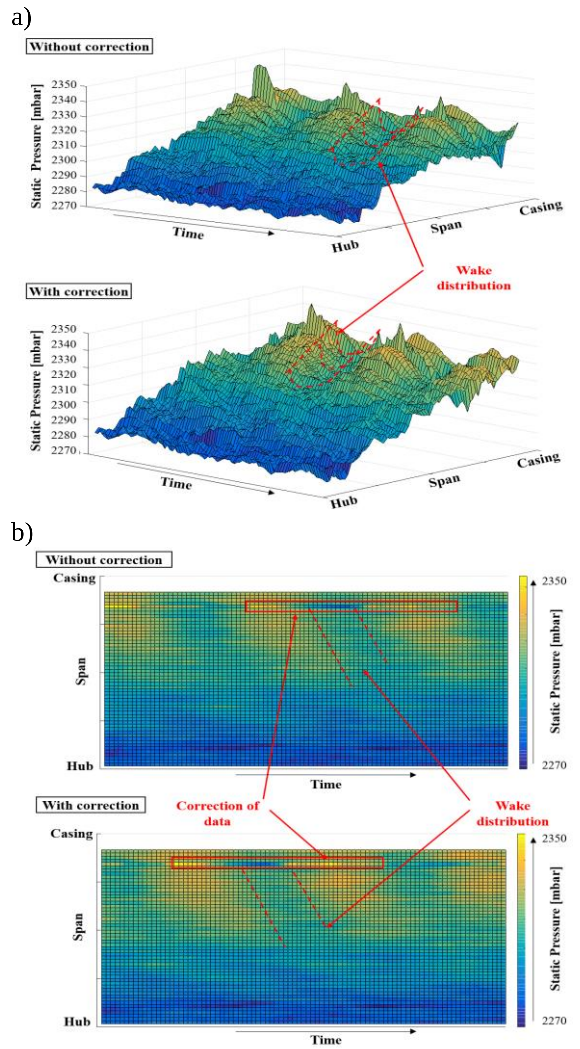

Figure 12: Corrected and uncorrected transient pressure distribution across span for p3 in OP1 a) 3D visualization b) top view

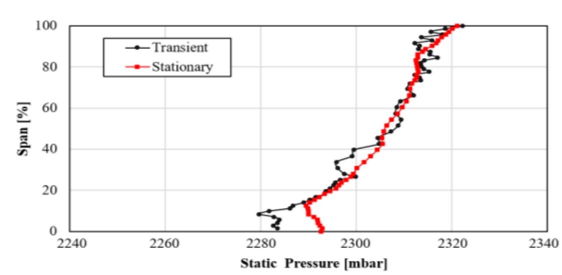

Figure 13: Comparison of transient and stationary pressure distribution

vortices. It has to be mentioned that the color maps has been changed compared to the three dimensional figures for purpose of illustration however it is set constant for all OP to keep comparability. Therefore the

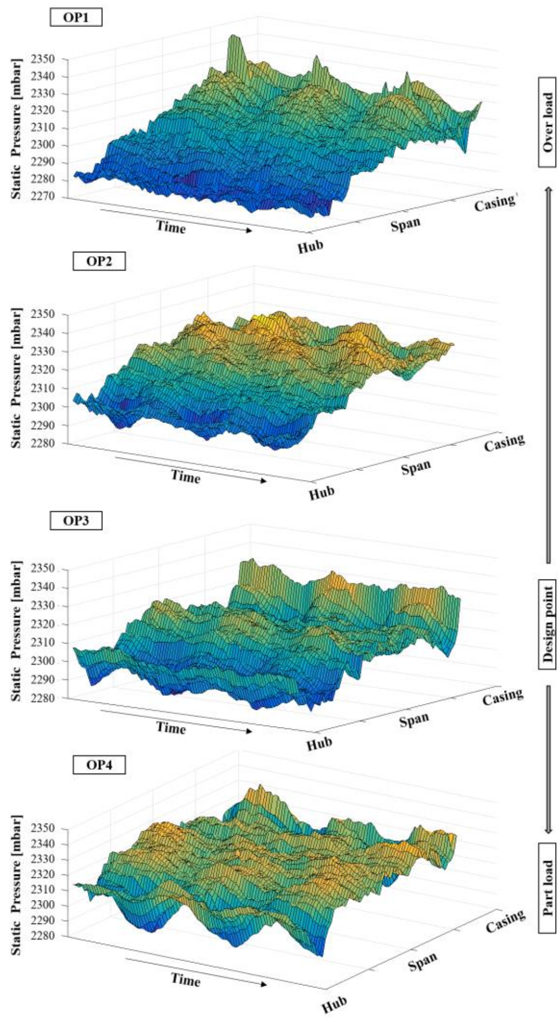

Figure 14: 3D plots of transient pressure distribution across span for all OP

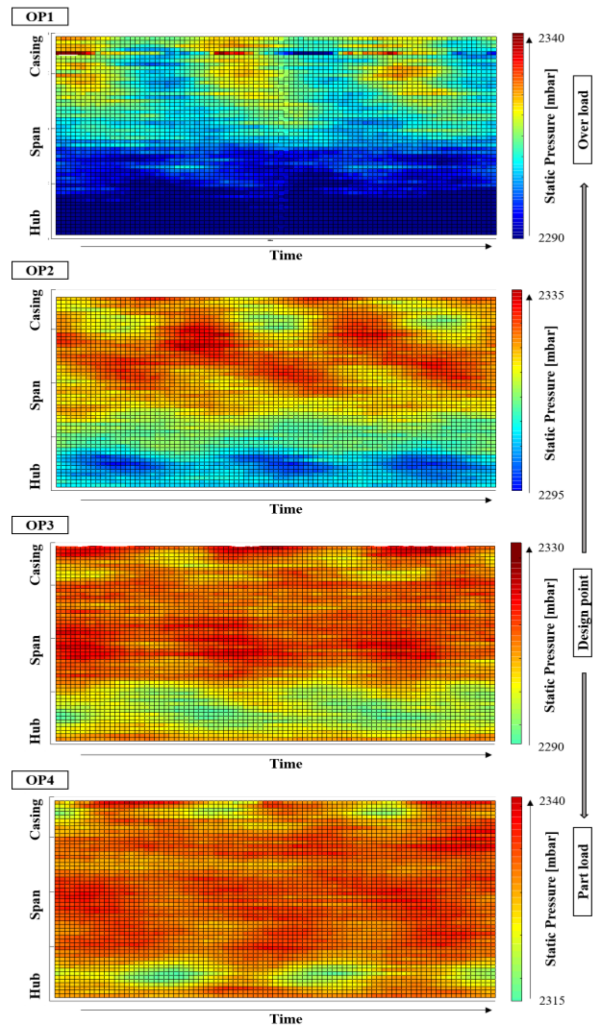

Figure 15: Top view of transient pressure distribution across span for all OP

reader may identify a region of enhanced turbulence for over load (OP1 and OP2) between the channel center and the casing. In part load (OP4) these phenomena can also be observed with less intensity.

In a next step, the five bore pressures can be transformed with equation (1) and (6) to the flow angle alpha to get a better understanding of the vortex behavior. It has to be outlined that the interpolation process is quite sensitive to even small pressure deviations between all holes thus it is necessary to run an ensemble averaging process in advance.

The resulting transient angle distribution for all OP is plotted in Figure 16. A area of large flow deflection is located close to the hub that is caused by the channel vortex that propagates in this area. One can also recognize the wake of the rotor blades that cause a sine curved shape at the highest angle values. Also a smaller vortex phenomenon can be observed close to the casing. The rotor influence on the incidence of the following stage is depicted in this area, too. The side view in the same figure (Figure 16) serves to interpret the amount of the angle distribution across the whole span.

This analysis of the flow at the outlet of the second stage has shown that the introduced wind tunnel calibration as well as the described post processing methods are a feasible solution to depict the occurring vortices and wake distributions of a complex flow field as it occurs in turbo machinery.

CONCLUSION

The present paper deals with the question of how to calibrate 5-hole-probes with transient pressure transducers located directly in the probe head. In addition, correction methods are introduced to post process the measured data in order to determine the correct flow field across the whole span.

Therefore a spherical 5-hole-probe head manufactured by Kulite (FAP-250) has was added to a stem and integrated into an existing probe adjusting device. A cranked design has been chosen to reduce the influence of the stem to the bore which are located at the upper part of the spherical probe head. This design feature requires several correction measures in the post processing to ensure correct interpretation of the flow field. The corresponding equations are given and explained in detail.

The probe has been calibrated in an open jet wind tunnel at Mach numbers of 0.1, 0.15 and 0.2 and an angular range of ±20° for yaw and pitch angle. The resulting calibration matrices lie in good accordance to validated data that was gathered with a stationary 5-hole probe.

Flow field measurements were conducted at the outlet of the second stage of a 2-stage axial turbine located at the Institute of Power Plant Technology, Steam and Gas Turbines, RWTH Aachen University. Four operating points have been investigated to see whether the probe measurements are feasible to interpret the flow structure of complex flow fields. The results clearly identify wakes and the change of vortices due to the different operating status. By applying the calibration factors to the pressure raw data the channel vortex and vortices close to the casing can be visualized however it has to be mentioned that ensemble averaging methods are required due to the high sensitivity of the calculation algorithms.

These findings justify the statement that the used probe and the introduced methods are appropriate to perform transient measurements in turbomachinery and to investigate the influence of different blading designs to the flow.

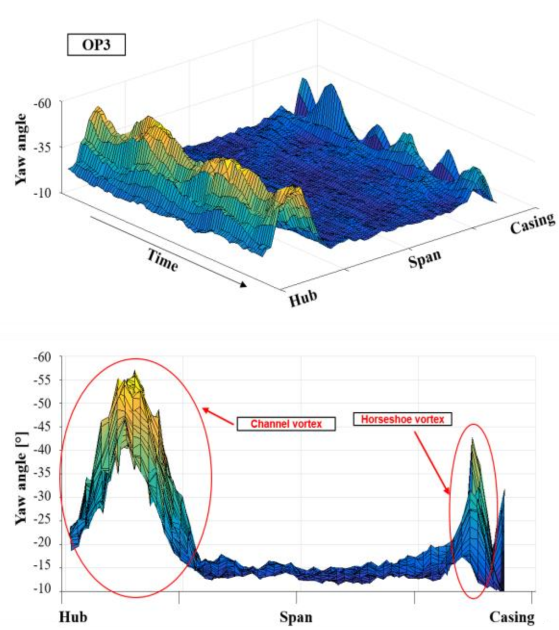

Figure 16: Transient angle distribution for OP3

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