IGV-ROTOR INTERACTIONS IN A 4-STAGE AXIAL COMPRESSOR

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ABSTRACT

Detailed experiments have been made in a 4-stage axial compressor of industrial design. The exit flow field of the rotor of the first stage was measured by hot-wire anemometry and fast-response pressure probes under design operating conditions. Tandem inlet guide vanes (IGV) are situated upstream of the first rotor.

Flow field results are presented for total pressure, massflux and swirl angle over a closely-spaced grid of probe locations in radial and circumferential directions in the absolute and rotating frame of reference. The tandem inlet guide vane row and stage 1 vane row are positioned peripherally for various settings (clocking).

Depending on the peripherical position of IGV and stator 1 the mean values for one rotor pitch varies by 1.5% for mass flow, 1.3° for swirl angle and 8.7% for total pressure.

Loss in total pressure at the rotor exit is a minimum, when the IGV row wakes enter the downstream rotor passage at about ¼ pitch from the suction-side. Blade and vane channels have similar pitchwise spacing.

1. INTRODUCTION

The initial design of a compressor blading is based on 2D computer codes for the meridional flow. These codes rely on models for trailing edge flow deviation, loss in total pressure and blockage effects due to airfoil wakes and endwall boundary layer. Improvement in the prediction of blockage is a major concern and initiated the present work.

This contribution centers on the measurement of the unsteady flow field at the outlet of the first-stage rotor (Fig. 1, plane 2) to investigate the influence of unsteady phenomena on the average quantities of the flow, which are used in design codes.

2. RESEARCH COMPRESSOR

These experiments have been made at the University of Bochum

NOMENCLATURE

Roman symbols
A amplitude, area, coefficient
B coefficient
c absolute velocity
E bridge output voltage
f frequency
h annulus height
K no. of ensembles
k current ensemble
kB blockage factor
kW threshold jet to wake
N rotational speed
n exponent
Ma rotor Mach number
m mass flow
p pressure
r radial coordinate
S no. of samples
s current sample
T temperature
t time coordinate
w relative velocity
z no. of blades, quantity

Greek symbols
\( \alpha \) swirl angle to axis
\( \Delta t \) sample rate
\( \varphi \) circumferential coordinate
\( \mu \) massflux
\( \rho \) density

\( \Pi \) pressure ratio
\( \omega \) angular velocity

Subscripts
ax axial
B blading
d dynamic head at inlet
eff effective
F fluid
geo geometric
IGV inlet guide vane
J jet
R rotor
red reduced to reference
ref reference
rel relative
St stage
t total
W hot-wire, wake

Superscripts
- periodical
+ random
- mass-, time-averaged

Abbreviations
CTA Constant-Temperature-Anemometry
PS pressure side
SS suction side
TE trailing edge
on a high-speed, 4-stage axial compressor blading of industrial design from DEMAG-DELAVAL (Fig. 1).

![Diagram of 4-stage axial compressor with tandem inlet guide vanes]

**Fig. 1: 4-stage axial compressor with tandem inlet guide vanes. Measurement plane \( \odot \) is the rotor exit of stage I.**

The inlet flow is straightened by a honeycomb and enters axially into the bladed channel. Between planes \( \odot \) and \( \odot \) there are two staggered rows of vanes with zero camber set to zero incidence for swirl-free flow into rotor 1 (Fig. 2). Usually tandem vanes offer the possibility of turning the flow for large angles at lower loss compared to single vane rows. This feature is not of concern here as the tandem inlet vanes merely create airfoil wakes typical for an unthrottled situation.

The average total pressure ratio per stage is \( \Pi_{s,0} = 1.17 \). With a relative tip Mach number of \( M_{a,rel} = 0.8 \) in rotor 1 the flow is subsonic throughout the blading.

An annular diffuser at the compressor outlet guides the flow from axial to radial direction through an orifice into a settling chamber. The nominal design test conditions of the compressor are:

- Reduced rotational speed: \( N_{red} = 11488 \text{ RPM} \)
- Reduced mass flow: \( m_{red} = 13.574 \text{ kg/s} \)
- Total pressure ratio: \( \Pi_T = 1.8 \)
- Inlet reference pressure: \( P_{ref} = 100000 \text{ Pa} \)
- Inlet reference temperature: \( T_{ref} = 288.15 \text{ K} \)
- Blade number: \( z = 22 \) (44) 23 24

Spindle-driven rings support the vanes and allow for peripheral positioning relative to the peripherally fixed radial traversing probes. Thus, measurements of the unsteady rotor exit flow field can be obtained with the IGV and the downstream stators set to several discrete circumferential positions.

### 3. INSTRUMENTATION

The individual operating points as well as the reference conditions are acquired by pneumatic pressure measurements. Circumferentially averaged measurements were done with pneumatic 3-hole probes and 5-hole probes including an NTC thermocouple, which allow for radial traversing (Jung and Eikelmann, 1995).

#### 3.1 Fast-response pressure transducer

Fast-response probes for total pressure are equipped with sensors EPI-127 made by Entran with a membrane diameter of 1.27mm. The sensor's resonance frequency lies at 500kHz according to manufacturer data. Shock tube testing of the probe resulted in 423kHz. The amplitude frequency characteristic leaves the 3dB-limit at 112kHz.

As the sensor is exposed to the investigated flow directly, secondary influences of the varying fluid temperature cannot be excluded. For that reason, the pressure transducer is equipped with an external temperature compensation in addition to the manufacturer's internal one (Cherret, 1990). The pressure can then be determined as a function of output voltage and voltage drop over a constant resistance, the latter being a function of the membrane resistance and the membrane temperature respectively. The entire measurement chain cuts off frequencies above 243kHz (analogue amplifier)

#### 3.2 Hot-wire probe

X-wire probes are used to measure the 2D flow vector. The wires are orientated in the blade-channel cross-section, so velocity and swirl angle can be measured. Due to the highly subsonic flow, the fluid's compressibility has to be taken into consideration. Therefore velocity and density are linked to the massflux \( \mu \) (Brunn, 1995).

The extended King's law for a compressible, non-isothermal flow includes the temperature difference between wire and fluid, as indicated by Eq. (1).

\[
E^2 = \left[A + B \cdot \mu^4\right] \left[T_w - T_c\right] \tag{1}
\]

The temperature difference is known from a stationarily measured, circumferentially-averaged radial distribution. This temperature correction is especially necessary when measuring in the endwall regions. With a known bridge voltage \( E \), and supposing an erroneously high fluid temperature, Eq. (1) results in an excessive massflux. Dissipation near the endwalls increases the fluid temperature. If the temperature distribution is assumed to remain constant, the resulting mass flow will be too low.

Sensors 55P61 and CTA-bridges 56C17 made by Dantec are in use (wire-diameter of 5µm). The frequency range of each wire was found with the built-in square-wave-current generator of each bridge and was always above 100kHz.

#### 3.3 Field measurement points

A notched disk on the compressor shaft sends a signal at every revolution through an inductive transmitter, which is used to initiate acquisition of time unsteady measurements. This guarantees, that acquisition of each signal will begin at the same rotor blade position. Each time record is digitized in time steps of \( \Delta t = 5\mu s \) (sampling frequency = 200kHz) by an A/D converter allowing for \( S_{max} = 256 \) samples (in power of 2). Thus, the entire time trace corresponds to 1.28ms or nearly 5½ rotor pitches. The first \( S = 227 \) of these 256 samples, corresponding in time to 5 rotor blade passings, are taken to contribute to the ensemble average, the remainder being discarded. In all, \( K = 50 \) time traces per ensemble are obtained phase-locked by the trigger, on which further statistical quantities can be derived. In radial direction, the traverse extends from 1% to 99% annulus height. Due to the size of the fast-pressure probes, the point nearest to the hub will be left out to avoid contact. Altogether the probes were traversed to up to 41 different radii with closer spacing near hub and casing because of increasing gradients in the flow.

\( K = 50 \) phase-locked time traces are acquired for each of the 41
radial positions resulting in 50 traces × 5 pitches = 250 samples for each field point. Based on Student’s probability density distribution this allows for 95% confidence corresponding to 2.5% relative error in the dynamic pressure.

The exploration of the IGV-rotor interactions is performed by shifting the IGV and stage 1 stator rows circumferentially relative to the probe by one pitch of the IGV. The IGV and stage 1 stators are both moved through the same angle so that their relative position is unchanged.

The pressure probe tests are repeated 17 times with stator positions stepping in equal intervals, across a distance corresponding to one IGV pitch. The hot-wire tests were performed at less positions corresponding to 11 steps over the same distance to reduce excessive hot-wire repair because of mechanical failures.

To analyze the frequencies Fast-Fourier transforms of the three distributions were calculated and are shown in Fig. 3, right. Beyond 9 times the blade frequency, the amplitudes drop below the probe’s precision limit Δp_{sensor}.

![Fig. 2: Tandem IGV, rotor and stator of the first stage of the 4-stage axial compressor. Controlled diffusion airfoils represented as NACA-65 thickness distribution here.](image)

3.4 Frequency response

When using time-resolved measuring techniques, it is important to verify their valid frequency range. To do this for the rotor exit field, the probe must be capable of following multiples of the blade-wake frequency. With a rotor blade number of z_R=23 and at nominal rotational speed this frequency is

\[ f_B = N \cdot z_R = 4.4 \text{kHz} \]  

Initially, no experimental data were available to determine the required measurement system frequency response. Therefore, numerical results for the 3D time-steady Navier-Stokes computation (Cornelius and Thiemann, 1992) have been used (Fig. 3, top).

After the first successful measurements (Fig. 3, bottom), experimental distributions at 3 annulus heights (10%, 50% and 90%) could be compared with the predictions. Their agreement at 10% annulus height is extremely good. Width and defect of the wake are almost identical. Discrepancies at the other radii can be explained with simplifications in the numerical simulation. Unsteady interactions and the conical inlet have not been implemented into the computation.

To analyze the frequencies Fast-Fourier transforms of the three distributions were calculated and are shown in Fig. 3, right. Beyond 9 times the blade frequency, the amplitudes drop below the probe’s precision limit Δp_{sensor}.

![Fig. 3: Total pressure distribution of numerical and experimental results (ensemble average) as well as amplitude frequency characteristics at 3 annulus heights at the exit of rotor 1.](image)

4. DATA REDUCTION

After transformation of output signals to the physical quantities, additional statistical data can be obtained. The change from the absolute to the rotating frame of reference involves indexing in the time trace and the corresponding peripheral positions.

4.1 Statistical quantities

All unsteady data rely on the current IGV position \( \Phi_{IGV,rel} \), the instant \( t \) (or, respectively, the rotor position \( \Phi_R=2\pi N t \)), the traversing immersion \( r \), and the ensemble \( k \):

\[ z = f(\Phi_{IGV}, t, r, k) \] (3)

After treatment of all \( K \) single measurements with the assumption of a pitch-periodic flow, the phase average and the random fluctuation are defined as follows:

\[ \bar{z}(\Phi_{IGV}, t, r) = \frac{1}{K} \sum_{k=1}^{K} z(\Phi_{IGV}, t, r, k) \] (4)

\[ z'(\Phi_{IGV}, t, r) = \sqrt{\frac{1}{K-1} \sum_{k=1}^{K} [z(\Phi_{IGV}, t, r, k) - \bar{z}(\Phi_{IGV}, t, r)]^2} \] (5)

By averaging the above quantities over multiple pitches, stationary average and stationary fluctuation levels are determined by:
Lastly, the periodic fluctuation is determined via Eqn. 8. It describes the standard deviation between stationary and periodic average and is an indication of the degree of periodic interaction:

$$
\bar{z}(\phi_{IGV}, r) = \frac{1}{S+1} \sum_{s=0}^{S} \bar{z}(\phi_{IGV}, t = s \cdot \Delta t, r)
$$

(6)

$$
\bar{Z}(\phi_{IGV}, r) = \frac{1}{S+1} \sum_{s=0}^{S} \bar{z}(\phi_{IGV}, t = s \cdot \Delta t, r)
$$

(7)

The variable $z$ can now be substituted by the known quantities such as total pressure $p$, massflux $\mu$ or swirl angle $\alpha$.

By superposing total pressure from the fast-response pressure transducer, and swirl angle and massflux from the hot-wire measurements with the steady-state total temperature from the 5-hole probe, velocity and density can be separated in an iterative procedure. Furthermore, total pressure, velocity and swirl angle of the rotating frame of reference can be calculated. This is allowed, because a stable operating point is investigated and influences caused by environmental fluctuations can be compensated in the data reduction.

4.2 Mass flow

The physical dependence of velocity and density in the hot-wire measurements in Eq. (1) can be used in another way to determine the mass flow through one rotor pitch. For this purpose the axial component of the massflux will be integrated over the traversed annular section as follows:

$$
\dot{m} = \int \mu_{ax} \cdot \cos \alpha \, dA = \int \mu \, dA
$$

(9)

As traversed area and through-flow area differ for hub and casing by 1%, the integral is evaluated by imposing the no-slip condition at the endwalls.

4.3 Blockage factor

Because of the no-slip condition and the loss-generating phenomena described previously, the regions near the endwalls and in the wakes have a decreased throughflow with respect to the undisturbed bulk flow.

The jet-wake model offers a scheme to separate both regions. Here, the wake area will consist of regions, where the local massflux is lower than the mass-average.

$$
\mu_{wx, w} \leq k_w \cdot \bar{\mu}_{ax} = k_w \cdot \frac{\dot{m}}{A_{geo}}
$$

(10)

The threshold between jet- and wake-region can be set to $k_w=90\%$ (Rohne and Banzhaf, 1990). Using numerical methods, area and mass flow of jet- and wake-regions can be calculated from the measured traverse grid. Now the effective area of jet and wake combined has to be found. The latter is defined as the area needed under the assumption that the wake region will carry a massflux $\bar{\mu}_{wx}$ to obtain the real wake mass flow $\dot{m}_{w}$.

$$
A_{eff} = A_j + A_{w, eff} = A_j + \frac{\dot{m}_{w}}{\bar{\mu}_{ax}}
$$

(11)

Finally the blockage factor can be defined as the ratio of the effective to the real through-flow area.

$$
k_w = 1 - \frac{A_{eff}}{A_{geo}}
$$

(12)

According to the wiggles in the $k_w$ distribution shown in Fig. 5 the uncertainty in the blockage appears to be 0.4%.

4.4 Probe positions relative to IGV and rotor 1

For a better understanding of the IGV-rotor interactions in the rotor exit flow field, all measurements made by circumferential-fixed probes are contributed to positions of IGV and rotor 1.

In Fig. 4 two examples of different rotor-to-stator positions are indicated. The left figure shows the IGV in its initial position with the rotor in trigger position (solid contour line).

$$
\phi_{IGV} = 0
$$

IGV

Rotor

Probe with rotor-position at trigger-event

$$
\phi_R = t = 0
$$

$$
\phi_R = \omega \cdot t = \phi_{IGV}
$$

Fig. 4: Transformation of measured data to the rotating frame of reference for rotor-positions $\phi_R=0$ and $\phi_R=\phi_{IGV}$

(Axial IGV-rotor gap not to scale)

At the time $t=0$ the rotor position is defined as $\phi_R=0$. For an identical position of IGV relative to rotor 1 the probe is at a different position $\phi_R$ relative to IGV and rotor 1 (broken contour line). Now stator and rotor are in the same position to each other as in the figure at left. Only the probe appears to have traveled against the sense of rotation.

4.5 Influences of positioning blades and vanes

Beside the mere change into the rotating frame of reference it is possible to detect errors by considering only one probe-to-stator position compared with the complete transformation. The open symbols in Fig. 5 show the influence of the peripheral positions of vanes to the probe averaged over multiples of rotor blade passing periods on the data aquired here.

If the investigation is restricted to one position of the probe relative to the IGV, then variations in the distributions occur due to interference with inlet guide vanes. Fig. 5d shows how the wake of an inlet guide vane is peripherically phase-shifted and how it influences the massflow at $\phi_{IGV,rel}=50\%$ by a deficit of 4% between the average value in time and pitch (solid symbol) to the average in time only.
Ia

V

IQ

—fl— measured in absolute frame of reference — transformed to rotating frame of reference centered between the rotor wakes and then will move to the pressure side. It will be displaced forward by the rotor merely by 13% of its pitch.

Trends in blockage factor developments cannot be associated with peripheral positions easily. The mass flow curve is not perfectly periodic, therefore decreases or increases of the mass flow due to drift in the calibration during an extensive time of measurements can be excluded.

Nevertheless the variations with different peripheral settings are considerable. At positions \( \varphi_{IGV,rel} = -40\% \) and \( \varphi_{IGV,rel} = +55\% \), the probe measures a mass flow deficit of up to 4% caused upstream by the 2nd row IGV wake, which will be chopped by the rotor repeatedly (see also the IGV wake in the \( w_{ax} \) distribution). Influences by the 1st IGV-row-generated wakes cannot be observed (compare 5a with 5d).

The comparison of mass flow and swirl angle leads to the conclusion, that the reduced mass flow can be attributed only to the term \( \cos \alpha \) in Eq. (9), whereas the massflux \( \mu \) should not be influenced by differing stator-probe-positions. This can be verified with Eq. (13), which is derived and simplified from Eq. (9) to yield

\[
\Delta m_{rel} = \frac{\Delta m_{ax}}{\mu_{ax}} = \frac{\Delta \alpha \cdot (-\mu \cdot \sin \alpha)}{\mu \cdot \cos \alpha} = -\Delta \alpha \cdot \tan \alpha \quad (13)
\]

By inserting the pitch swirl angle \( \bar{\alpha} \), as well as the maximum deviation \( \Delta \alpha \) of Fig. 5 into Eq. (13), we nearly get the corresponding relative mass flow difference as shown in Fig. 5.

The highest pressure increase happens corresponding to mass flow deficits, as shown in Fig. 5d. Similar total pressure developments can be noticed for the 1st IGV-row-generated wake at \( \varphi_{IGV,rel} = +5\% \), while the mass flow seems not to be influenced. The distribution of the total pressure in Fig. 5 has not yet been correlated with a physical interpretation.

5 ROTOR-STATOR INTERACTIONS

The following sections deal with the rotor exit flow fields in the rotating frame of reference associated with varying IGV positions (e.g. Fig. 5, closed symbols).

5.1 Mass-averaged quantities

The quantities displayed in Fig. 5 by the open symbols originate from the input data for the transformation into the rotating frame of reference, shown in Fig. 5 by -U-. The latter represent mass-weighted averages of multiple rotor pitches as a function of the current IGV position, as indicated for the blade-to-blade sections at the bottom in Fig. 5. When observing the rotor in its frame of reference, the IGV will rotate from left to right.

It is obvious, that all curves corresponding to the rotating frame vary less than their counterparts in the absolute frame. With \( z_{IGV} = 22 \) tandem vanes and \( z_{IGV} = 23 \) rotor blades, IGV and rotor have almost identical pitch, therefore every rotor pitch swallows the wakes of a tandem vane, independent of their position to each other. The mass flow varies from 0.3% up to 2.3% with respect to the nominal value from the previous section 2.

Also swirl angle and, consequently, the absolute through-flow in the closed-symbol distributions should not vary according to Eq. (13), whereas the total pressure distribution changes more. A cyclic slope is noticeable in the closed-symbol distribution with a minimum at Fig. 5: Blockage, mass flow, swirl angle and total pressure (top) as well as \( w_{ax} \) (bottom) measured in the absolute frame of reference (open symbols) and transformed to the rotating frame of reference (closed symbols) over one IGV pitch from \(-42\% \leq \varphi_{IGV,rel} \leq +58\%\). (Axial IGV-rotor gap not to scale)

The distributions in the absolute frame of reference depend on different stator positions relative to a circumferentially-fixed probe. The current stator position is shown in Fig. 5, bottom, and shows the situation at 50% immersion of the probe. \( p \) and \( E \) are mass-averages of several rotor pitches, which move peripherally. \( \alpha \) is derived from the averaged velocity triangles.

The phase-shifted transport of the IGV wakes through the following rotor can be seen in Fig. 5 (see also Gallus et al., 1979). There are shown in Fig. 5a-d 4 different cross-sectional IGV-rotor positions and the corresponding distributions of the axial velocity midspan at the rotor exit. The dominating rotor wakes are always present with the 2nd IGV-row wake passing through. In Fig 5a the wake is nearly
where the mass flow reaches its maximum. Thus, kinetic energy and potential energy from pressure balance each other.

In conclusion it can be noticed, that the rotating blade row achieves its maximum total pressure at $\varphi_{IGV,rel}=+9\%$, when the wake generated upstream enters the pitch at about $\frac{1}{4}$ from the suction side (Fig. 5d). This is supported by a decay of the blockage-factor in the same situation. Obviously blockage effects will be more pronounced in total pressure drop than in the swirl angle or the mass flow.

5.2 Random and periodical total pressure distribution

The distribution of the random fluctuations (Eq. 7) are used to detect regions of loss (Cherret et al., 1994). Mainly the total pressure fluctuations are investigated, as the velocity should behave analogously. As a proof, Fig. 6 represents both. Under the assumption of incompressibility with Eq. 14, the fluctuations of massflux and total pressure can be compared.

$$p_*=\mu' \frac{2\mu}{\mu'} - \bar{\mu}$$

As shown in Fig. 6, this scheme can be used for the bulk flow. Fluctuations in the bulk flow caused by vane-blade interactions (Eq. 8), Fig. 6, triangular symbols) show lower levels than random fluctuations (Eq. 7), Fig. 6, square symbols).

5.3 Distributions of axial velocity-density

The preceding distributions of sections 4 and 5 displayed the IGV-rotor interaction as mass-weighted average (Fig. 5) or IGV-pitch-average (Fig. 7). The following Fig. 8 presents the axial velocity-density $\mu_*$ (Eq. 9) at the exit of the rotor by 8 instantaneous views equivalent to 8 IGV positions relative to the rotor.

Additionally the corresponding relative mass flow and the blockage factor are shown below each frame. 4 out of the 8 views can be associated with the blade-to-blade views in Fig. 5. The trailing edges of all relevant blades and inlet vanes are indicated.

In all distributions (Fig. 8a-h) the corner stall at the hub, the rotor wake across the entire annulus height and the tip leakage vortex near the casing appear as regions with mass flow defects. A small region near the suction side with maximum through-flow exists, independently of the current IGV position.
Fig. 8: Instantaneous pictures of the axial velocity-density at the rotor exit. Blade-to-blade views in Fig. 4, bottom, can be associated with Fig. 5a = Fig. 8f; Fig. 5b = Fig. 8a; Fig. 5c = Fig. 8c; Fig. 5d = Fig. 8e.

The rotor wake will deviate from the indicated trailing edge, as with increasing annulus height the distance between edge and measuring plane increases.

The sequence starts with $\varphi_{IGV,rel}=0\%$ (Fig. 8a). With an observer in the rotating frame of reference, the upstream IGV will move from left to right against the rotor speed. The nearly axially transported IGV wake emerges on the pressure side. The bright area on the suction side represents the undisturbed bulk flow. Wake and bulk flow move through the rotor passage without influencing tip leakage vortex and corner stall. This is indicated by the bulk flow, where the casing endwall at 92% annulus height will not penetrate the vortex region.

The IGV wakes have their minimum massflux near the hub (Fig. 8d-g) which extends nearly to midspan. In Fig. 8e-g, the hub leakage vortex of the 2nd IGV row has left the corner stall region and can be detected. In these views, the wake generated by the 2nd IGV-row is situated at midpitch. Similar results show Fig. 8b-d for the 1st IGV-row.

When the wakes of the rotor and the IGV are in phase, the effective wake increases its width, but will be less pronounced, as it can also be seen in the $w_{m}$ distribution in Fig. 5c (Johnston and Fleeter, 1996). The wake does not extend anymore from hub to tip in Fig. 8d. This will be accompanied by a maximum of the blockage factor.

5.4 Validation

The integral mass flow (Eq. 9) can be compared with the mass flow determined by the orifice. The averaged relative mass flow as shown in Fig. 5 amounts to 1.3% above the design value.

Circumferentially-averaged measurements were done with pneumatic 3-hole probes on the above-mentioned 41 radii and with larger 5-hole probes outside the endwall boundary layer in the bulk flow including a NTC-thermocouple with respect to their larger extent only for the primary flow (Fig. 9, $w_{rel}$). They were taken at the circumferential probe position $\varphi_{IGV,rel}=-8\%$ (see e.g. Fig. 5b, open symbols).

Swirl angles obtained with the 3-hole probe are also used to pre-align the applied fast-response pressure and hot-wire probes. This had to be done to prevent incidences on the fast-pressure probe which cause a systematic error and the flow to leave the valid calibration range for hot-wire probes.

Distributions of the circumferentially-averaged swirl angle, axial velocity and total pressure are presented in Fig. 9. The bright shading indicates the extension from minimum in wakes to maximum in jets.
across the rotor pitch. The dark shading area shows the variation range of rotor pitch-averaged values. Both cover one IGV-passing period.

The dark shading distributions compare well with the open-circle symbols signifying pneumatic probe data. The width of the dark shading varies little over the entire channel height.

However the absolute discrepancies, shown as bright shading, will be affected by the rotor wakes, as they are skewed due to deficits of velocity and total pressure. The bandwidth of the absolute swirl angle is skewed towards larger angles because of nearly constant relative flow angle and velocity defects in the relative flow.

The least discrepancies are at 92% annulus height, where, as indicated in Fig. 7, left, the casing endwall region begins. With decreasing distance between trailing edge and measuring plane in direction to the hub, the wakes will be more pronounced. This causes increasing absolute variations. The bandwidth reduces at 10% and at 92%, where endwall boundary layer influences starts.

6 CONCLUSION

The preceding analysis can be concentrated into the following statements:

- With only one radial scanning, the rotor exit flow field cannot be described adequately (Cherret et al., 1994). As shown in this paper, depending on the circumferential position, discrepancies of 4% in mass flow or 4° of swirl angle can appear.
- Due to similar pitch in IGV and rotor, there are only minor variations of mass flow and flow vector in the rotating frame of reference, independent of their position to each other. The lowest total pressure losses and the least blockage occur, when the IGV-generated wake enters the rotor passage ¼ of the pitch from the suction side.
- The tip clearance vortex and the hub corner stall of the rotor are the predominant loss effects, whose intensity and extent will not be influenced by IGV-rotor interactions.

REFERENCES


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