Paper 4

Session 1 - Cascade Testing

PANDA - A NEW DATA ACQUISITION SYSTEM FOR WAKE AND PROFILE PRESSURE DISTRIBUTION MEASUREMENTS AT THE HIGH SPEED CASCADE WIND TUNNEL

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Abstract:

At the High-Speed Cascade Wind Tunnel of the University of the Federal Armed Forces Munich advanced measuring techniques have been established for the investigation on new design concepts for bladings of multistage axial turbomachines.

In this paper the hard- and software of a new, fully computer controlled measurement system for wake and profile pressure distribution measurements are described. Beside a three axis traversing system for wake probes and a temperature measurement system three different pressure measurement systems have been installed to achieve minimal errors within the possible pressure range to be measured in test cases from 0 hPad up to about 1000 hPad. All pressure transducers can be calibrated on-line without any manual change on the electrical or pneumatic set-up. For getting an optimal starting-position for the wake traverse the difference between the upstream and downstream total pressure can be shown on the control terminal continuously while the probe is traversed manually. In addition, a monitoring of the total temperature and of the static and total reference pressure is provided by the software for a check of the actual Mach and Reynolds number as well as for a check of reaching steady-state condition. After the measurement is carried out on-line evaluation and a graphical display of the results are provided by the software.

A lot of tests were made and show the excellent accuracy of the system. In addition wake measurements were carried out with three different probes. The results of these measurements will be discussed.

Nomenclature

a) Symbols:

A	[mm^2]	area vertically to the flow
ax	[mm]	coordinate in axial direction
BETAS	[°]	stagger angle
c_p, CP	[-]	pressure distribution coefficient, see equation (2.6)
DP	[hPa]	static pressure difference $\lvert p_1 - p_2 \rvert$
DPT	[hPa]	total pressure difference $p_{t1}-p_{t2}$
e_M/l, EM/L	[-]	relative distance of wake measurement plane axially downstream of the blade trailing edge plane
F(x)	[x]	error of x
H	[mm]	blade height
I	[A]	current
k_1, k_2	[hPa], [hPa/V]	coefficients of a linear pressure transducer characteristic
l, L	[mm]	profile chord length
Ma, MA	[-]	Mach number, see equation (2.4)
n	[min^{-1}]	number of revolutions
P	[kW]	electrical power
P_1	[kW]	electrical power of first vacuum pump
P_2	[kW]	electrical power of second vacuum pump
p, P	[hPa]	static pressure
p_t, PT	[hPa]	total pressure
q, Q	[hPa]	dynamic pressure
R	[J/kg/K]	gas constant
Re, RE	[-]	Reynolds number, see equation (2.5)
S	[K]	Sutherland constant (S = 110.4 K)
t/l, T/L	[-]	pitch/chord ratio
T_t, TT	[K]	total temperature
Tu, TU	[%]	degree of turbulence
U_0	[V]	zero offset of a pressure transducer
U_x	[V]	transducer output voltage measuring the pressure x
u/t, U/T	[-]	relative circumferential coordinate, wake traverse axis
$\dot{V}$	[m^3/s]	air flow rate
w	[m/s]	flow velocity
x/l, X/L	[-]	relative profile coordinate, blade chord direction
z, Z	[mm]	coordinate in spanwise direction
ß, BETA	[°]	flow angle
$ß_s$	[kg/m/s/K$^{0.5}$]	Sutherland constant ($ß_S = 1.458 \cdot 10^{-6}$ kg/m/s/K$^{0.5}$)
ζ_V	[-]	total pressure loss coefficient, see equation (2.1)
κ	[-]	specific heat ratio
ρ	[kg/m^3]	flow density
Ω, OMEGA	[-]	axial velocity density ratio, see equation (2.3)

b) Indices, Suffixes:

1	upstream condition
2	downstream condition
2th, 2TH	downstream condition for isentropic flow (theoretisch)
K	related to the pressure tank of the wind tunnel (Kammer)
kr	critical (kritisch)
u, U	within the wake traverse plane
ref	reference quantity
Umg	barometric condition (Umgebung)
Vk	related to settling chamber (Vorkammer)
x/l	local profile surface quantity

c) Abriviations:

BCD	binary-coded digit
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrttechnik
DS	pressure side (Druckseite)
FHP	five hole probe
FS	full scale
hPad	hecto pascal, differential pressure
hPag	hecto pascal gauge
IEEE	Institut of Electrical and Electronical Engineers
NP	Neptun probe
PANDA	program for an automatiziation of wake and profile pressure distribution measurements including evaluation (Programm zur Automatisierung von Nachlauf- und Druckverteilungsmessungen incl. Auswertung)
PANDAPLT	plot program for PANDA results
Profil	cascade name
psid	pounds per square inch, differential pressure
RAM	random access memory
SS	suction side (Saugseite)
UniBw	University of the Federal Armed Forces (Universität der Bundeswehr)
V-Nr.	test number (Versuchs-Nummer)
WP	wedge probe

1. Introduction

The real flow in an axial turbomachine is highly three-dimensional, compressible, viscous and unsteady. A very customary simplification is the plane cascade model. This model allows the two-dimensional theoretical treatment of basic flow phenomena and can be tested in cascade wind tunnels.

The High-Speed Cascade Wind Tunnel of the University of the Federal Armed Forces Munich (Fig. 1.1) is installed in a tank, which can be evacuated up to 40 hPa and pressurized

up to 1200 hPa, so that an independed variation of Mach and Reynolds number is possible. The rebuilding of the wind tunnel, which was formerly in operation at the DLR in Braunschweig, was finished in November 1985 (see /1/). After some calibration tests the establishment of different measuring techniques started simultaneously with the research work (see /2/). One of the main topics of this work are investigations on the losses of turbomachine bladings and on the boundary-layer behavior.

From the beginning of the experimental work on linear cascades, wake and profile pressure distribution measurements were carried out for the determination of the losses. Furthermore, this standard measuring technique makes it possible in most cases to get information about the reason of the losses and the condition of the boundary layer with a sufficient accuracy. The experimental procedure and the evaluation of wake and profile pressure distribution measurements on cascades were fundamentally described in /3/ for the first time. Compared to the procedure and evaluation used formerly at the DLR Braunschweig (see /4/) only some small changes were carried out referring to the quantities to be measured. Therefore a short describtion will be given.

As reported at the last symposion in Oxford (see /2/) a new data acquisition system was designed and installed at the High-Speed Cascade Wind Tunnel. Extensive tests especially on the accuracy of the pressure measurements within the possible pressure range in test cases from 0 hPad up to about 1000 hPad resulted in a redesign of the pressure measurement system. The optimization of the system has been completely finished and the new data acquisition system is now in work for one year.

2. Principals of wake and profile pressure distribution measurements at the High-Speed Cascade Wind Tunnel

The purpose of wake measurements is the determination of local and integral cascade parameters i.e. total pressure loss coefficient, static pressure rise coefficient and flow deviation. For a comparison of different cascades the quantities of homogeneous upstream and downstream conditions are required for the determination of these parameters. Due to the fact, that the flow through an ideal cascade is periodical in the circumferentional direction, it is sufficient to look only at one blade passage of the cascade.

The upstream flow field of a blade passage can be seen as a homogeneous field compared to the downstream flow field (see Fig. 2.1). Therefore the upstream conditions can be measured in one point of a plane parallel to the inlet plane of the cascade. The total pressure p_{t1} is measured with a Pitot probe, which has a distance of 50 mm from the side wall and about one cord length from the inlet plane of the cascade. In the same distance from the cascade the static pressure p_1 is determined using static wall tappings. The total temperature T_{t1} is evaluated as the mean value of four temperatures $T_{t,Vk,i}$ measured by resistance thermometers in the settling chamber behind the main flow cooler (see Fig. 1.1). With the assumption of an adiabatic flow this temperature corresponds to the temperature in the inlet plane of a cascade.

In contrast to the homogeneous upstream flow field, the inhomogeneous downstream flow field is a function of the axial and circumferential direction. Homogeneous conditions are reached only far downstream of the outlet plane. The measurements are carried out by traversing a probe through the wake of the center blade of the cascade in approximately 40% chord distance e_M axially downstream of the blade trailing edge plane (see Fig 2.1). At every probe position the lokal total pressure $p_{t2,u}$ and the static pressure $p_{2,u}$ are recorded. If the size of the probe is small enough, also the exit flow angle $\beta_{2,u}$ is determined at every measurement point within the traverse plane. Otherwise the exit flow angle can be measured only at points of no disturbance in the outer wake regions.

The measured quantities of the inhomogeneous downstream flow field have to be converted in quantities of a homogeneous flow field by applying the conservation laws of mass, momentum and energy on the control volume shown in Fig. 2.1. This evaluation (see /4/, /5/) leads to the total pressure loss coefficient which is defined as

$$\zeta_{V,ref} = \frac{p_{t1}-p_{t2}}{q_{ref}} \qquad (2.1)$$

and to the static pressure rise coefficient, which is defined as

$$\frac{\Delta p}{q_{ref}} = \frac{|p_1-p_2|}{q_{ref}} \qquad (2.2)$$

as well as to the exit flow angle β_2. Finally the axial velocity density ratio is determined which is defined as

$$\Omega = \frac{A_1}{A_2} = \frac{\rho_2}{\rho_1}\cdot\frac{w_2}{w_1}\cdot\frac{\sin\beta_2}{\sin\beta_1} \qquad (2.3)$$

and which should not differ more than 5% of the value $\Omega = 1.0$ to indicate a two-dimensional flow.

The reference quantities in the equations (2.1) and (2.2) depend on the tested cascade type:

	Compressor	Turbine
p_{ref}	p_1	p_K
q_{ref}	$q_1 = p_{t1} - p_1$	$q_{2th} = p_{t1} - p_K$
$T_{t,ref}$	$T_{t1} = T_{t,Vk}$	$T_{t1} = T_{t,Vk}$

Corresponding to this, the reference Mach and Reynolds number are Ma_1 und Re_1 in the case of compressor cascades and Ma_{2th} und Re_{2th} in the case of turbine cascades. The Mach and Reynolds number are determined from the measured quantities total temperature, dynamic pressure and static pressure with the equations

$$Ma_{ref}^2 = \frac{2}{\kappa-1}\cdot\left[\left[1+\frac{q_{ref}}{p_{ref}}\right]^{\frac{\kappa-1}{\kappa}} - 1\right] \qquad (2.4)$$

$$Re_{ref} = \left[\frac{\kappa}{R}\right]^{\frac{1}{2}}\cdot\frac{1}{\beta_S}\cdot\frac{Ma_{ref}\cdot p_{ref}\cdot\left[T_{t,Vk}\cdot\frac{1}{1+((\kappa-1)/2)\cdot Ma_{ref}^2}+S\right]}{\left[T_{t,Vk}\cdot\frac{1}{1+((\kappa-1)/2)\cdot Ma_{ref}^2}\right]^2} \qquad (2.5)$$

Beside the mentioned integral cascade parameters for describing the performance of a cascade the corresponding local quantities total pressure loss coefficient $(\Delta p_t/q_{ref})_u$, static pressure rise coefficient $(\Delta p/q_{ref})_u$ and exit flow angle $\beta_{2,u}$ can be determined and plotted versus the relativ traversing coordinate u/t. In addition the local downstream Mach number $Ma_{2,u}$ may be calculated using eq. (2.4) with $q_{ref} = q_{2,u}$ and $p_{ref} = p_2$.

The profile pressure distribution is measured using static pressure tappings on the suction and pressure side of the center blade or better of the blades adjacent to the center blade. For the graphical display of the distribution normally a non-dimensional coefficient is defined as

$$c_{p,ref}(x/l) = \frac{p_{x/l} - p_{ref}}{q_{ref}} \qquad (2.6)$$

This pressure distribution coefficient is plotted versus the relativ profile coordinate in blade chord direction x/l.

Summarizing, the following quantities have to be measured for wake and profile pressure distribution measurements:

<table>
<tr><th>Wake measurements</th><th>Profile pressure distribution measurements</th></tr>
<tr><td>z-, u- and ß-coordinate
of the wake probe</td><td rowspan="2">$\Delta p_{x/l} = (p_{x/l} - p_{ref})$</td></tr>
<tr><td>$q_{1,u} = (p_{t1} - p_1)_u$ *)
$\Delta p_u = |(p_1 - p_2)|_u$
$\Delta p_{t,u} = (p_{t1} - p_{t2})_u$</td></tr>
<tr><td colspan="2">$T_{t,Vk,u}$
$p_{Umg,u}$
$(p_{Umg} - p_{ref})_u$
$q_{ref} = (p_{t1} - p_{ref})_u$</td></tr>
</table>

*) addititional quantity to be measured only in the case of turbine cascades

With the barometric pressure p_{Umg} the absolute values of the pressures $p_{ref,u}$, $p_{t1,u}$, $p_{1,u}$, $p_{t2,u}$ und $p_{2,u}$ can be determined from the measured differential pressures. The index u in this terms indicates, that the pressures were measured at the time of the wake probe position u. By integration over the traverse range, in general one blade spacing, non-stationary effects can be eliminated.

3. Data acquisition system

3.1 Hardware

The heart of the new data acquisition system is a multi user, 32 bit computer Perkin Elmer 3203 with 4 MB main storage. Beside a plotter and a matrix printer four alphanumerical and two graphical terminals are connected with this host computer of the test facility (see Fig. 3.1). Additionally there is a connection to the host computer of the University and one to the host computer of the department of aerospace engineering. The measuring and control instruments for different measuring techniques can be connected with the computer via an IEEE-488 bus. This connection guarantees a great flexibility, because a change in the set-up can be done very easily. Furthermore each instrument can be used in common for different measuring techniques without disconnection.

The aim of the design of the new data aquisition system for wake and profile pressure distribution measurements was a set-up, which allows fully computer controlled measurements with on-line evaluation and graphical display of the test results. The hardware of this system can be divided into the following three systems:

- traversing system
- temperature measurement system
- pressure measurement system containing three subsystems

These systems can be used seperately for different measuring techniques and controlled by the host computer with program modules designed for decreasing the time needed for new software development (see /6/).

3.1 Traversing system

The traversing system for the wake measurements has three, three-phase current motor driven axis and two additional, manual adjustable axis for moving the wake probe in the right distance of the cascade and inclining the circumferential axis parallel to the cascade exit plane. The three motor driven axis are (see Fig. 3.2):

- z-axis = linear axis in spanwise direction
- u-axis = linear axis in circumferential direction
- ß-axis = axis of rotation round the z-axis

A system of position display and control units in the control room of the test facility was

designed for computer or manual remote controlled movement of a probe behind a cascade. The position display units for each axis are connected to optical position measurement units at the traversing system and show the position relativ to a user defined zero point. A traversing of a probe can be done manually using the front panel of the control units or computer controlled via an IEEE-BCD/relay interface. A detailed description of the system is given in /7/. Using the program modules from /6/ for a computer controlled traversing the positioning accuracy is 0.04 mm for the linear axis and 0.02° for the rotation axis.

3.1.2 Temperature measurement system

As mentioned in chapter 2 the total temperature of the upstream flow of a cascade is calculated as the mean value of four temperatures measured with resistance thermometers in the settling chamber of the wind tunnel. The thermometers are connected with transducers in the control room of the test facility (see Fig. 3.3). The mean value of the four temperature signals is used as the instantaneous value for the digital temperature controller of the wind tunnel as well as for the computer controlled measurement (The scanner in the set-up shown in Fig. 3.3 makes a flexible use of the voltmeter for other measurements possible.).

3.1.3 Pressure measurement systems

The most extensive part of the new data aquisition system for wake and profile pressure distribution measurements is the system for the determination of all relevant pressures. Due to the fact, that the static pressure at the High-Speed Cascade Wind Tunnel can range from 40 hPa to 1200 hPa, the pressures to be measured (see chapter 2) can range from 0 hPad to about 1000 hPad. The results of extensive tests with a first designed measurement system based on fast ±15 psid multichannel transducer moduls showed that a great accuracy within this pressure range can only be achieved by different pressure measurement systems. The redesign led to three different systems:

- differential pressure measurement system
- profile pressure measurement system
- pressure measurement system for non-standard techniques

Fig. 3.4 gives a general view of the integration of these systems into the data acquisition system. In addition the integration of a digital barometer is shown in this figure as well as the integration of two digital pressure controllers used for the calibration of the differential pressure measurement system and the pressure measurement system for non-standard techniques.

3.1.3.1 Differential pressure measurement system

If the differential pressures (see chapter 2) shall be measured all over the mentioned range with about the same accuracy, differential pressure transducers have to be selected with different ranges. An ideal instrument for this purpose is the multichannel digital pressure transmitter PRESSURE SYSTEM INCORPORATED (PSI) DPT-6400 designed for modularity and operation through the front panel as well as through the IEEE bus. A built-in microprocessor executes an operating system containing programs which provide all control, acquisition and interfacing functions for the instrument. Pressures can be measured with a scan rate up to 2800 readings/sec. The number of averages to be taken by the instrument for each pressure reading can be set from 1 to 16. The configuration used at the wind tunnel contains 6 pressure scanners with each 4 differential pressure transducers in the ranges ±10" WC, ±1 psid, ±2.5 psid, ±5 psid, ±10 psid and ±15 psid. The transducers are silicon integrated circuit type.

A zero and span or only a zero calibration of all transducers is supported by the operating system of the DPT-6400. The microprocessor calculates the slope and intercept of the characteristic curves and stores it in a battery-backed RAM. The pneumatic design of the measurement system should permit a calibration with connected measurement pressures. But tests showed that this capability is only given in cases of pressures greater than the barometric pressure. Due to the fact, that the measurement pressures at the High-Speed Cascade Wind Tunel are normally lower than the barometric pressure, the calibration of the transducers can only be carried out before test runs.

Fig. 3.5 gives a general view of the pneumatic and electrical design of the differential measurement system as part of the data acquisition system. The calibration pressures for the transducers with smaller ranges up to ±2.5 psid are supported by a digital pressure controller DRUCK DPI-500 with an accuracy of ±0.07 hPa. The second pressure controller EPR-2 as part of the pressure measurement system for non-standard techniques supports the calibration pressure for the other transducers with an accuracy of ±0.3 hPa (see /8/). All instruments are connected via the IEEE bus with the host computer, so that a calibration can be carried out through the control terminal of the data acquisition system.

The relative errors in the pressure readings are shown in Fig. 3.6 based on an accuracy of ±0.25% FS. For pressures greater than 8 hPa the errors are less than 0.7%. Measurements after several calibrations demonstrate this high accuracy up to pressures of 1000 hPa. But the accuracy of the local and integral cascade parameters can not be seen from this representation, because these quantities are functions of more than only one measurement pressure.

As an example the error of the local total pressure loss coefficient has been calculated. The maxium error F can be determined from the equation

$$F(\zeta_{v,ref,u}) = \left[\frac{[F(\Delta p_{t,u})]^2 + [\zeta_{v,ref,u}\cdot F(q_{ref,u})]^2}{q_{ref,u}^2}\right]^{1/2} \qquad (3.1)$$

and is shown in Fig. 3.7 assuming that the total pressure difference $\Delta p_{t,u}$ is measured with a ±1 psid transducer. Down to q_{ref} = 45 hPa maximum error of only ±0.004 occurs. For lower dynamic pressures the total pressure difference $\Delta p_{t,u}$ should be measured with a ±10" WC transducer for reaching this high accuracy. Reproduced wake measurements with a turbine

cascade at dynamic pressures of q_{ref} = 200 hPa and q_{ref} = 20 hPa (see Fig. 3.8) including new calibrations of the pressure transducers demonstrate that the real accuracies are not higher than the calculated. Furthermore these tests shown that the integral total pressure loss coefficient can be determined with an error less than ±0.002.

3.1.3.2 Profile pressure measurement system

For the measurement of a lot of pressures with the same order of magnitude there are two different measurement systems available: The first one is the Scanivalve system based on a pneumatic multiplexer used for connecting the measurement pressures sequentially to the one existing transducer. The advantage of this system is the same measurement error of all pressures. On the other side the scan rate of the multiplexer is limited to about 20 readings/sec. The alternative measurement system consists of modules with several transducers and an electronical multiplexer. There are miniature modules available with 64 channels and built in power supply, amplifier and multiplexer with a scan rate up to 100 000 readings/sec. Both systems measure the pressure towards a common reference pressure. Also as a matter of principle an on-line calibration is possible with both systems.

With regard to a minimum error of the pressure distribution coefficient defined with equation (2.6) a Scanivalve system as well as a transducer module system was tested within the pressure range of the wind tunnel.

The accuracy of a pressure measurement depends strongly on the accuracy of the transducer calibration. But using a Scanivalve system a calibration is not necessary for the determination of the pressure distribution coefficient. Assuming a linear transducer characteristic the equation (2.6) can be written as

$$c_{p,ref} = \frac{p_{x/l} - p_{ref}}{p_{t1} - p_{ref}} = \frac{k_1 + k_2\cdot U_{\Delta p}}{k_1 + k_2\cdot U_q} \qquad (3.2)$$

If the zero offset U_0 is measured at each cycle of the pneumatic multiplexer by connecting the reference pressure also to one input port of the multiplexer, equation (3.2) can be simplified to

$$c_{p,ref} = \frac{k_2\cdot(U_{\Delta p}-U_0)}{k_2\cdot(U_q-U_0)} = \frac{U_{\Delta p}-U_0}{U_q-U_0} \qquad (3.3)$$

This shows that no calibration is necessary. The validity of the assumptions made for equation (3.3) demonstrates Fig. 3.9: The characteristics of the tested ±10 psid pressure transducers are indeed very linear (upper diagram) and the drifts of the zero offset during a measurement cycle are negligible (lower diagram). Therefore the accuracy of the pressure distribution coefficient depends only on the transient response of the pressure transducers after each single scan of the pneumatic multiplexer.

Investigations on this response were carried out by simulating a sudden change of pressure up to $\Delta p = \pm 175$ hPa and recording the transducer output voltages. Fig. 3.10 shows the results of the worst Scanivalve transducer tested. The response time is significant greater in cases of negative pressure changes. The lower diagram in this figure represents the resultant errors for a scan rate of 1 reading/sec. With these data the error of the pressure distribution coefficient can be calculated using the equation

$$F(c_{p,ref}) = \left[\frac{F(p_{x/1} - p_{ref})^2 + [c_p \cdot F(q_{ref})]^2}{q_{ref}^2} \right]^{1/2} \quad (3.4)$$

The result for negative sudden pressure changes is shown in Fig. 3.11 assuming a scan rate of 1 reading/sec and an error of the dynamic pressure $F(q_{ref}) = 0.1$ hPa, which is the greatest value for positive pressure changes from Fig. 3.9. For the interpretation of this error diagram it must take into account, that in general sudden pressure changes of more than $\Delta p = \pm 25$ hPa don't exist during a scan cycle of the pneumatic multiplexer, because the profile pressures are measured in the order of the location on the blade surface. For these sudden pressure changes of $\Delta p = \pm 25$ hPa the diagram demonstrates the excellent accuracy of the pressure distribution coefficient determined via a Scanivalve measurement system all over the possible range of the dynamic pressure at the wind tunnel.

Obviously these accuracies can not be achieved using multichannel transducer modules with only one pressure range. Extensive tests with a measurement sytem based on PRESSURE SYSTEM INCORPORATED ESP-32 modules with ±15 psid transducers (see /2/) demonstrated that an accuracy of only ±3.1 hPa can be reached (see /9/). This value includes the errors of all parts of the measurement system and the errors of calibration.

Profile pressure distribution measurements on a turbine cascade were carried out simultaniously with both measurement systems. The distribution in the left diagram of Fig. 3.12 represents the results for a Reynolds number $Re_{2th} = 5 \cdot 10^5$ and a Mach number $Ma_{2th} = 0.59$, i.e. a dynamic pressure $q_{2th} = 100$ hPa. The agreement ist quite well. But the pressure distribution for a Reynolds number $Re_{2th} = 1 \cdot 10^5$ and the same Mach number $Ma_{2th} = 0.59$, i.e. a dynamic pressure $q_{2th} = 20$ hPa, demonstrates in the right diagram clearly the effect of the worse accuracy of the multichannel transducer system as well as the effect of the different transducer errors. Even pressure distribution coefficients $c_p > 1$ were evaluated on the pressure side of the profile. The reason is the meantioned high error of ±3.1 hPa according to the low pressure values in this test case ($q_{2th} = 20$ hPa).

Due to the fact, that a profile pressure measurement system with multichannel transducer modules of different ranges would dramatically increase the complexity of the data acquistion system, a new measurement system was designed for profile pressure distribution measurements based on two Scanivalve transducers with a range of ±5 psid (see Fig. 3.13). With this system 96 pressures can be measured, i.e. 92 static profile pressures, because one input port of each transducer is needed for the measurement of the zero offset and one for the measurement of the dynamic pressure.

Finally it should be mentioned that the multichannel transducer modules were integrated in the data acquistion system as a pressure measurement system for non-standard techniques.

3.2 Software

An extensive software named PANDA operates the described data acquisition system and was designed for modularity and flexibility to the various test conditions. The program implemented on the host computer of the test facility provides all control and acquisition functions needed for wake and profile pressure distribution measurements on turbine or compressor cascades. The process of these measurements is controlled by the user via a terminal with graphical representation capability, so that the results of a measurement can be displayed on the screen immediately after the data acquisition and on-line evaluation is finished.

PANDA consists of the following program modules (see Fig. 3.14):

- program modules for the input of all non-measurable quantities needed for the control of the measurements and for the evaluation including a module for the printer output of all input data
- program modules for the calibration of the differential pressure measurement system and/or the multichannel transducer system and for the printer output of the coefficients of all transducer characteristics
- program module for the control of wake and profile pressure distribution measurements including data acquisition, evaluation and graphical display of the results
- program module for off-line evaluations of wake and profile pressure distribution measurements
- program module for a single scanning with all pressure transducers of the data acquisition system

Before PANDA starts a measurement the user has to inform the program of all non-measurable quantities. These quantities are seperated into three data blocks:

- cascade data, i.e cascade name and type, stagger angle, pitch/chord ratio and chord length as well as the coordinates of the static pressure tappings in blade chord direction
- data of the experimental set-up, i.e. inlet flow angle, installation angle and axial distance of the wake probe from the trailing edge cascade plane, height of the profiles and of the test section and name of the used turbulence generator as well as code numbers for all pressure transducers needed for the identification of the quantities which shall be measured with them
- test data of the next test which shall be carried out, i.e. test number, desired values of the total temperature, Mach number and Reynolds number, number of static profile pressures to be measured and number of wake measurement points as well as the spacing of the wake measurement points (the wake traverse can range from one to more blade spacings with a maximum number of 99 measurement points; each blade spacing can be divided into three parts with different spacings of the measurement points)

To achieve a minimum of time needed for the input of these data each data block is stored in files which are read by the program so that the user has only to change the uncorrect values.

The second program module which has to start before carrying out measurements, is the calibration module. This program module contains subroutines for the remote controlled zero or full - i.e. zero and span - calibration of the differential pressure measurement system as well as for the full calibration of the multichannel transducer modules. Because of the pneumatic design of these measurement systems and of the data acquisition system no change in the set-up is needed for the calibration.

After the execution of the mentioned program modules the user can start the module carrying out the wake and/or profile pressure distribution measurements. In the case of a wake measurement the first step of this program module is the positioning of the wake probe in the first measuring point of the traversing plane. If no coordinate can be input by the user because the position of the wake is unknown, PANDA provides a monitoring of the total pressure loss $(p_{t1}-p_{t2})_u$ while the user traverses the wake probe manually so that the starting position of the wake measurement can be determined.

Then the desired values of temperature, Mach number and Reynolds number as well as the resultant values of the static and dynamic reference pressure is output on the screen of the control terminal. Furthermore the actual values of these quantities are measured continuously and shown so that the variance can be seen as well as the reaching of steady-state conditions can be proved. If the desired flow conditions are reached the user can start the measurement.

First the wake measurement is carried out. If a probe is used which has to be traversed into the downstream flow direction for the determination of the exit flow angle, the program stops at the user defined wake measurement points so that the probe can be traversed manually using a U-tube as an indicator instrument. The profile pressure distribution measurement follows by scanning all input ports of the Scanivalve system. Finally the measurements with the multichannel transducer modules are carried out if needed.

All measured data are stored in a user defined file and the evaluation is automatically started. The results are output on the printer as well as plotted on the screen. Also a plotter output is provided by PANDA (Fig. 3.15). In addition a plot program named PANDAPLT was designed especially for comparative graphical display of results from test runs in which a geometrical or aerodynamic parameter of a cascade was variegated (see /10/).

4. Wake measurements with different probes

As mentioned in chapter 2 the exit conditions of a two-dimensional wake flow of cascade profiles may by described by the three parameters total pressure, static pressure and flow angle. These parameters change in the circumferential (coordinate u) and in the axial direction of the cascade front (Fig. 2.1). For wake measurements it is very important to get all these quantities in a small test volume.

Fig. 4.1 shows three different probes which are used for wake measurements at the High Speed Cascade Wind Tunnel. The wedge and the Neptun probe (see /11/) were designed at the DLR in Braunschweig. Both probes use an equalization of pressure on two holes for the

directional sensing. In case of the wegde probe two holes under an angle of 45 degrees are utilized. The Neptun probe has two parallel tubes which are cut under an angle of 45 degrees against the tube axis and are in the same line as the total and static pressure holes. Both probes were calibrated in the cascade wind tunnel.

The five hole ball end probe was designed and calibrated at the University of Aachen and provides information about total pressure, static pressure and the direction of a three-dimensional flow (see /12/).

To use the five hole probe for standard wake measurements in the cross section, comparative tests behind a turbine cascade were carried out with these three probes for different Mach and Reynolds numbers. Fig. 4.2 shows the results of two test cases. A good agreement can be seen for all results picked up with the wegde and the Neptun probe. The exit flow angle measured with the wegde probe can only be determined in the undisturbed flow, because the readings within the wake cannot be accurate, due to the fact that the angle-holes lay ±0.9 mm out of the probe center line (see /11/).

The four static pressure holes of the ball end probe (ø 2.6 mm) have the same distance of 0.9 mm of the center hole, though the results of this probe have to be seen very critical. The integral total pressure loss coefficient differs only 0.003 (see DPT/Q2th in the legends of the diagramms in Fig. 4.2). That is obvious, because for the total pressure losses only the center hole is used when the probe is nearly adjusted in the exit flow direction.

With the assumption of two dimensional exit flow no total pressure gradient exists on the horizontal holes No. 0, 1 and 3 of the probe (see Fig. 4.1), which are used for the determination of the local Mach number and the static pressure rise coefficient. But the results show, that the local Mach number and the static pressure rise coefficient are significantly lower. A reason may be the calibration, which was made at higher Reynolds numbers.

Compared to the results picked up with the Neptun probe the exit flow angle $\beta_{2,u}$ shows an overswinging in the wake flow, because of different total pressures at the wake positions of the two holes No. 2 and 4 (see Fig. 4.1). A correction method (see /13/) was tested, but for a small band width of the exit flow angle within the wake the method failed. For a greater band width the correction shows an insignificant improvement (Fig. 4.3).

The integral cascade parameters versus Reynolds number in Fig. 4.4 shows a negligible variance in the exit flow angle. Also the total pressure loss coefficient shows only small differences. But the static pressure rise coefficient and accordingly the axial velocity density ratio differs significantly for wake measurements carried out with the five hole probe relative to the other probes at lower Reynolds numbers.

5. Conclusion

At the High Speed Cascade Wind Tunnel of the University of the Federal Armed Forces Munich a fully computer controlled measurement system for wake and profile pressure distribution has been established. Extensive tests of this system especially of the pressure measurement systems has shown a high accuracy within the range of pressures to be measured up to about 1000 hPad: Differential pressures from 8 hPa to 1000 hPa can be measured with an error less than 0.7%. The pressure distribution coefficient can be determined with an accuracy of better than ±0.004 for dynamic pressures down to 45 hPa and with an accuracy of better than ±0.01 for dynamic pressures down to 16 hPa.

The software PANDA operating the data acquisition system was designed for modularity and flexibility to the various test conditions. The program provides all control and acquisition functions as well as on-line evaluation and graphical display of the results. Also the calibration of the pressure transducers can be carried out with this program without any change in the electrical or pneumatic set-up.

For wake measurements a comparative test of three different probes - a wedge, a Neptun and five hole ball end probe - was carried out. The results show the excellent accuracy of the wedge and the Neptun probe, which were especially designed for use in cascade wind tunnels. A reason for the disappointing static pressure determination with the five hole probe at lower Reynolds numbers may be, that the probe has been calibrated only at high Reynolds numbers.

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test section data:

- Mach number : $0.2 \le Ma \le 1.05$
- Reynolds number : $0.2 \cdot 10^6\ m^{-1} \le Re/l \le 16.0 \cdot 10^6\ m^{-1}$
- degree of turbulence : $0.4\% \le Tu_1 \le 7.5\%$
- upstream flow angle : $25° \le \beta_1 \le 155°$
- blade height : 300 mm
- test section height : 235 mm - 510 mm

supply units:

- evacuating unit : P_1 = 30 kW, P_2 = 20 kW
- boundary layer suction (centrifugal compressor) : P = 155 kW
- additional air supply (screw compressor) : P = 1000 kW

wind tunnel data:

- AC electric motor : P = 1300 kW
- axial compressor : 6 stages
- air flow rate : $\dot{V}_{max}$ = 30 m³/s
- total pressure ratio : $(p_{t1}/p_K)_{max}$ = 2.14
- number of revolutions: n_{max} = 6300 min⁻¹
- tank pressure : p_K = 0.04 - 1.2 bar

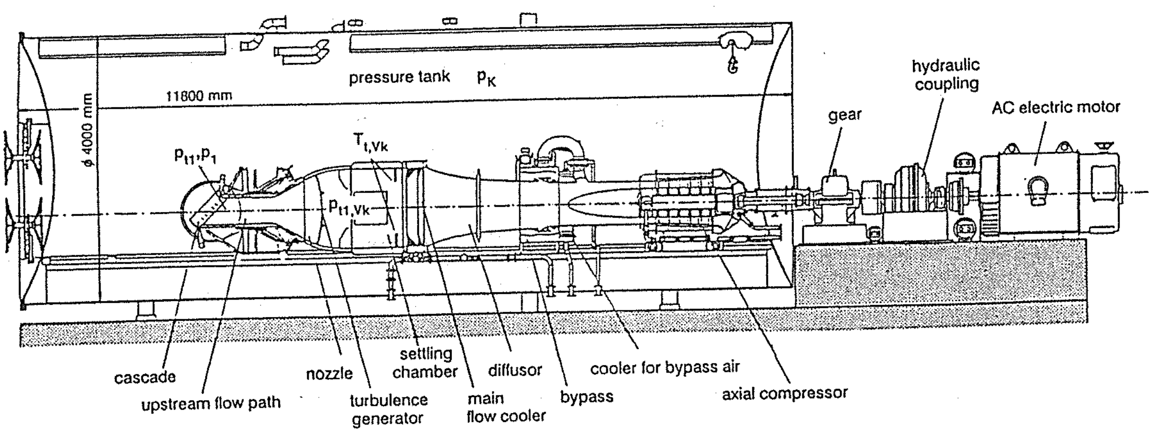


Fig. 1.1: The High-Speed Cascade Wind Tunnel

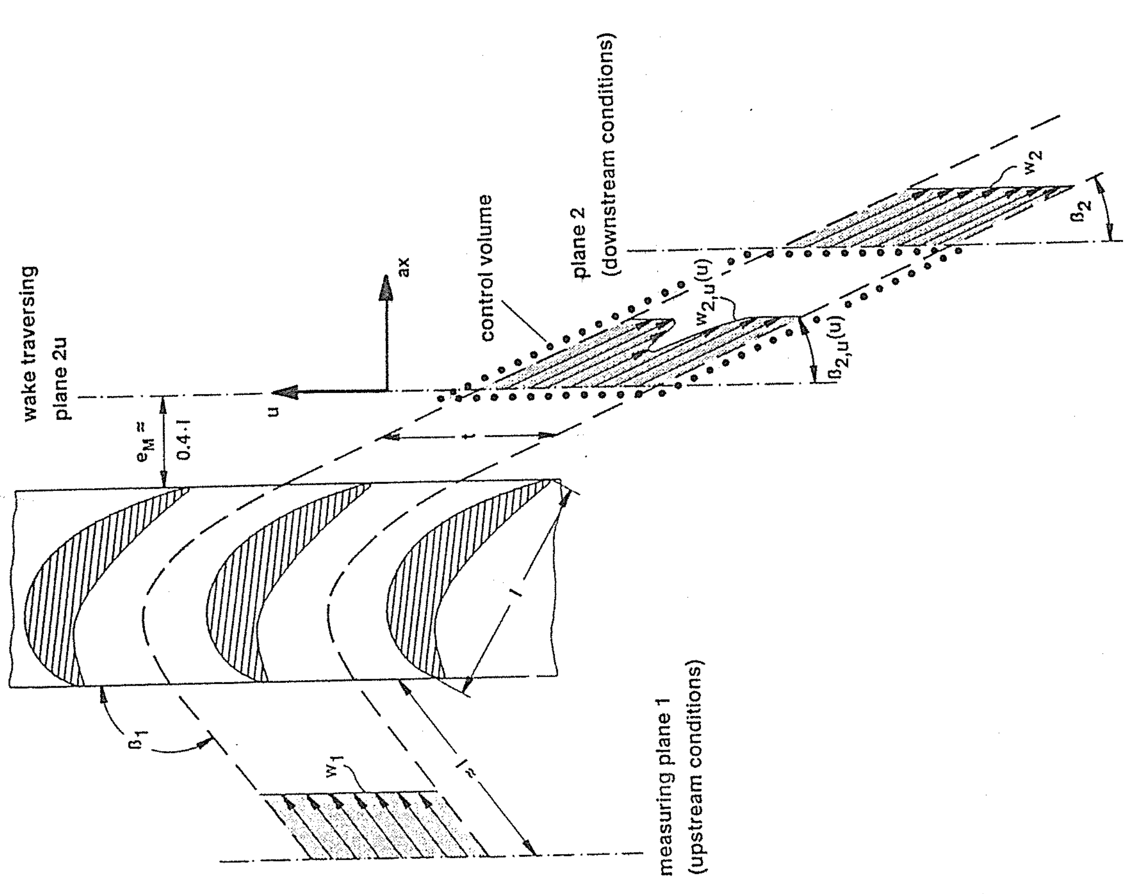


Fig. 2.1: Principles of wake measurements

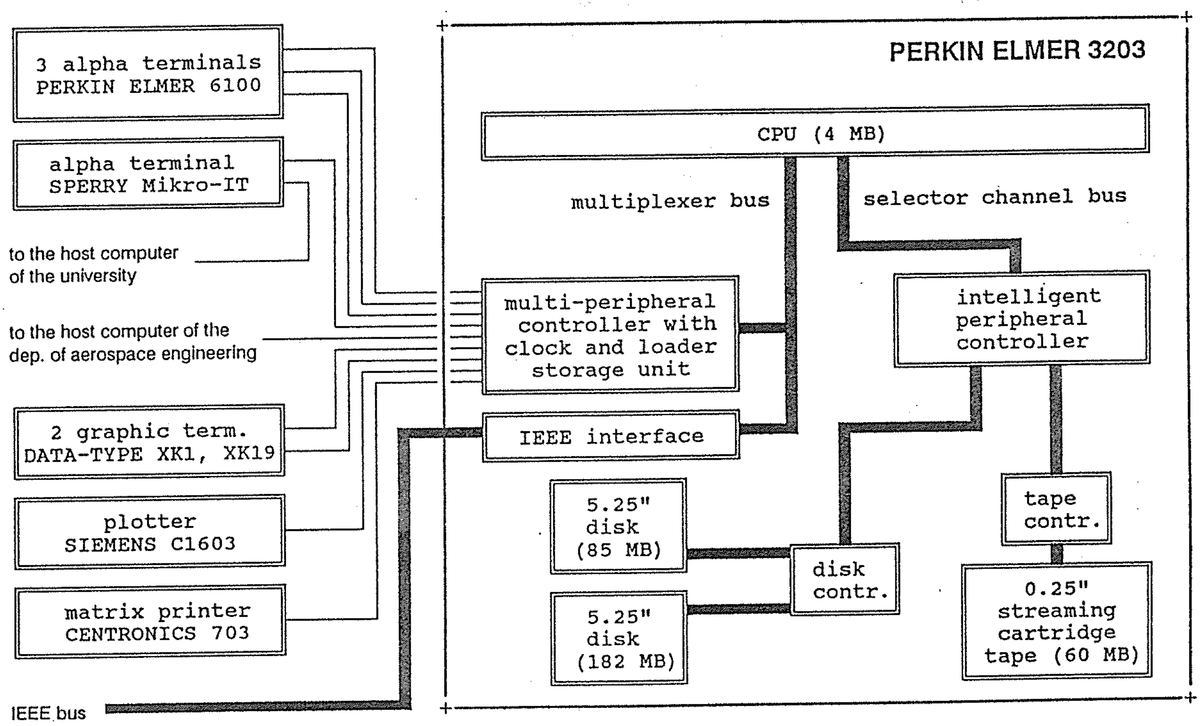
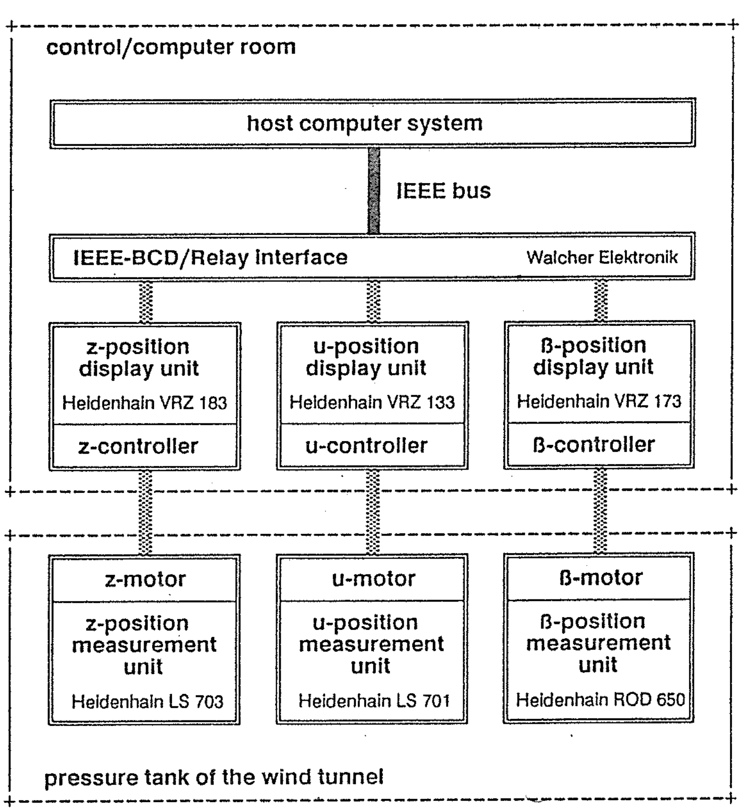


Fig. 3.1: Block diagram of the host computer system of the test facility



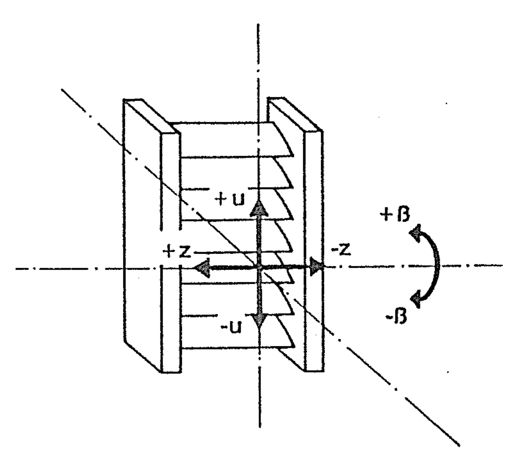


Fig. 3.2: System of traversing coordinates and block diagram of the traversing system

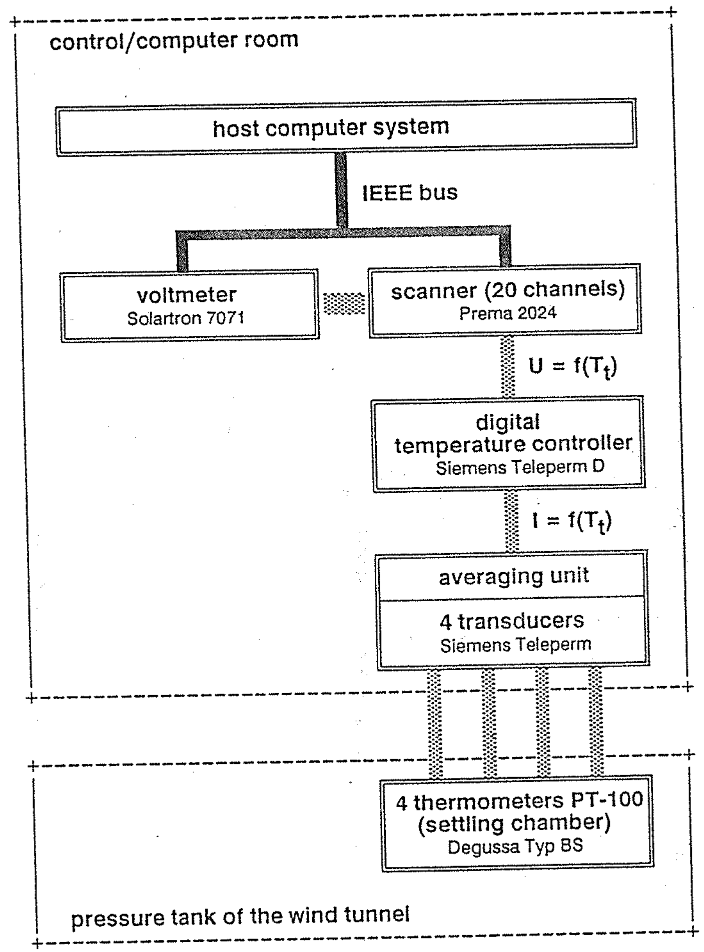


Fig. 3.3: Block diagram of the temperature measurement system

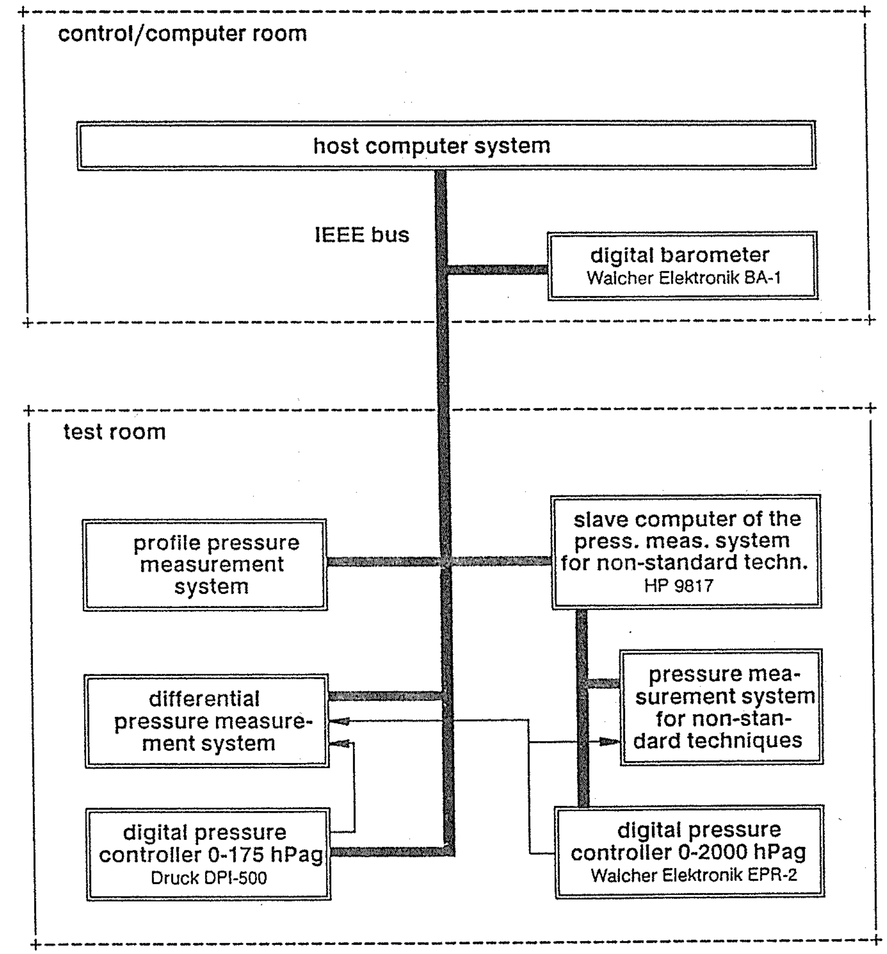


Fig. 3.4: Block diagram of the pressure measurement systems

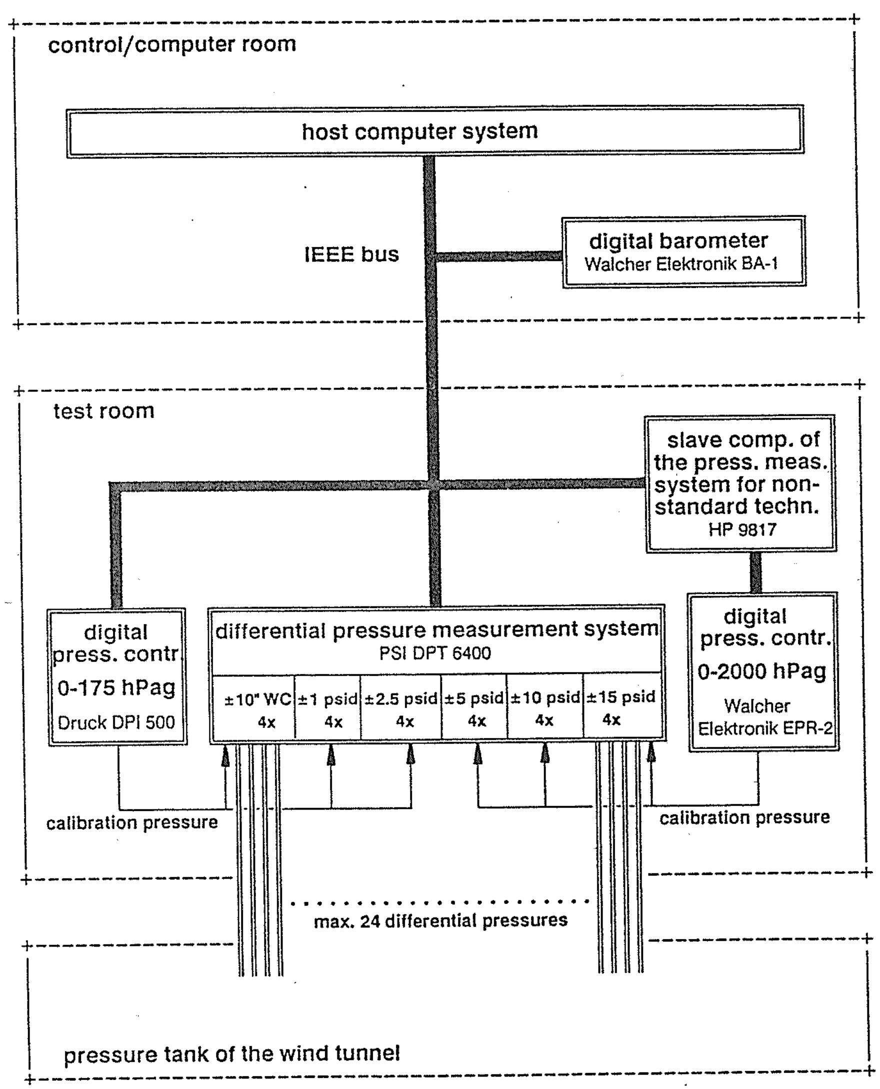


Fig. 3.5: Block diagram of the differential pressure measurement system

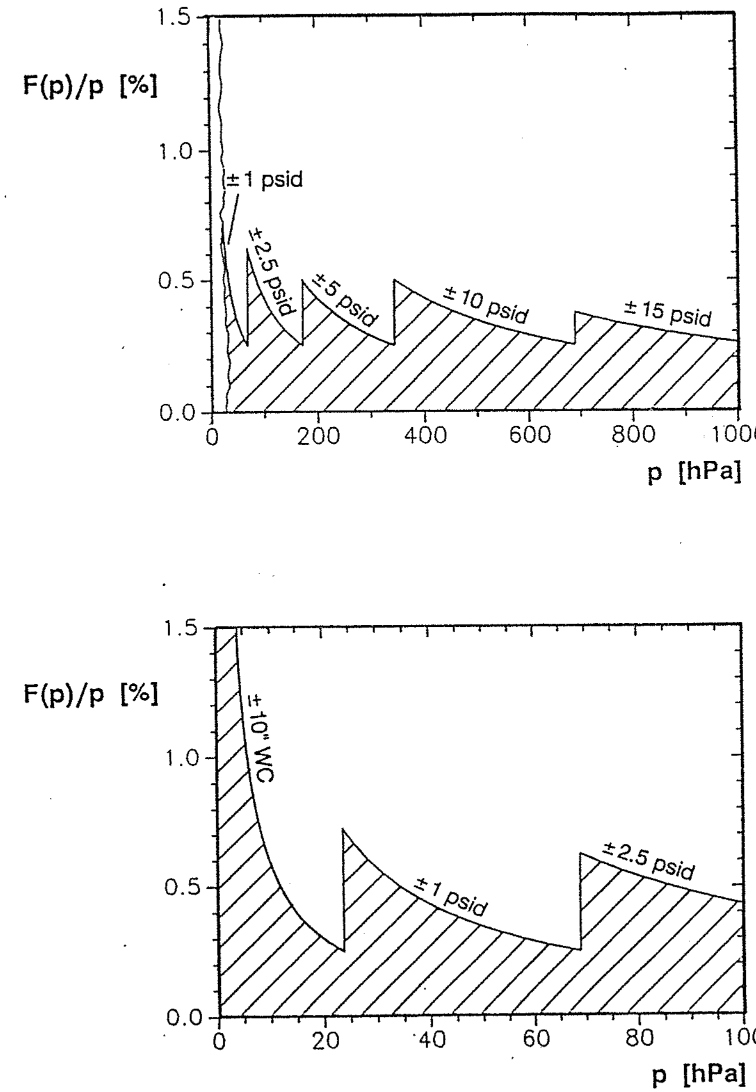


Fig. 3.6: Accuracy of the differential pressure measurement system

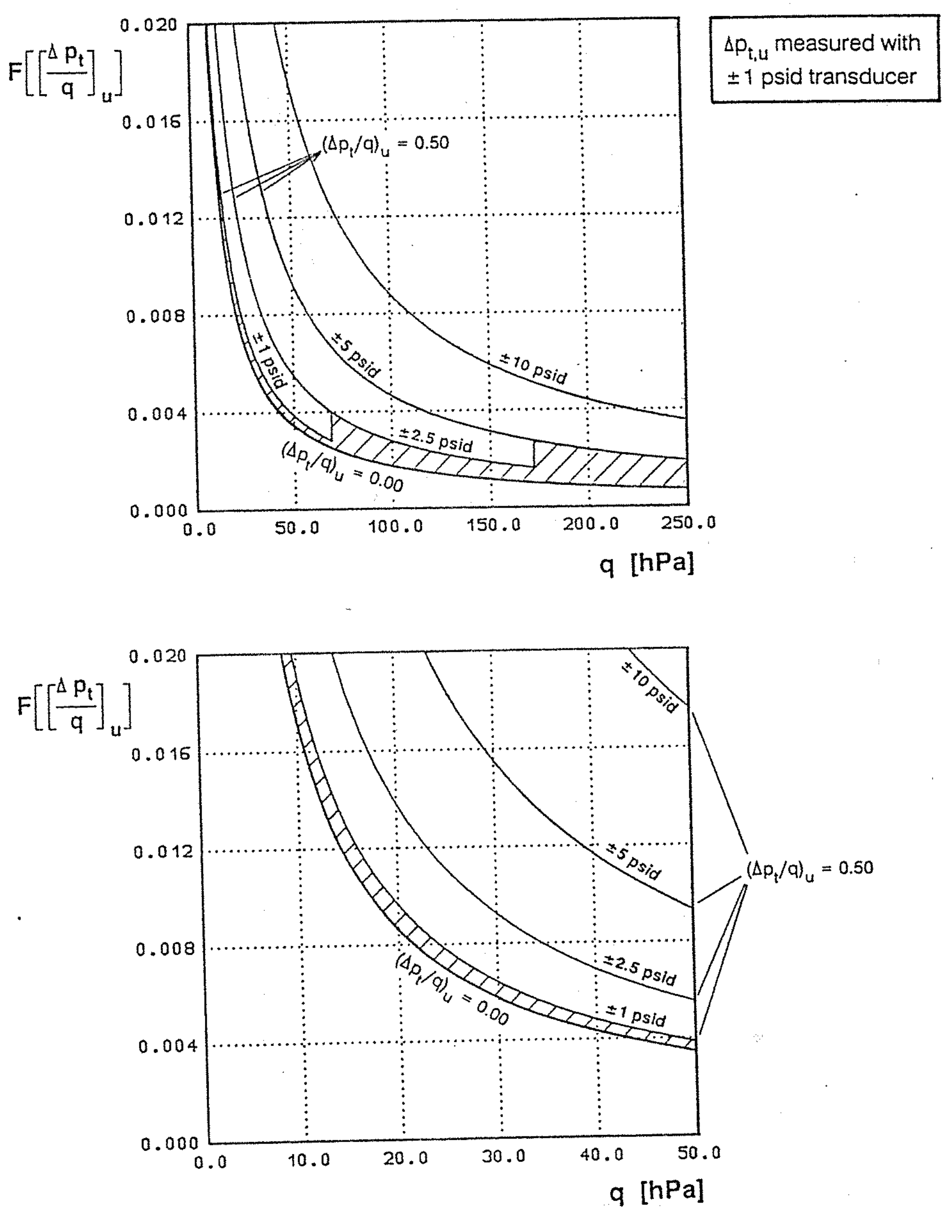


Fig. 3.7: Accuracy of the local total pressure loss coefficient

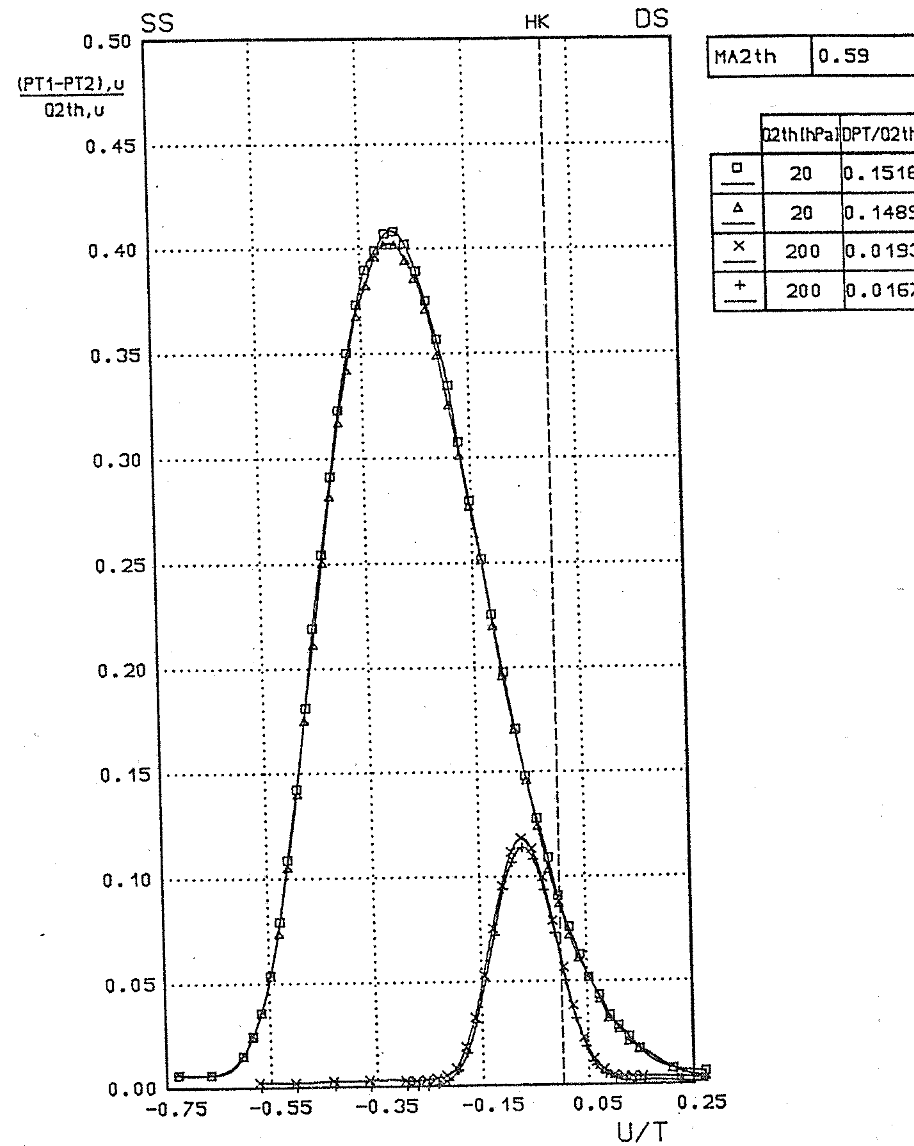


Fig. 3.8: Reproduced wake measurements on a turbine cascade (local total pressure loss coefficient)

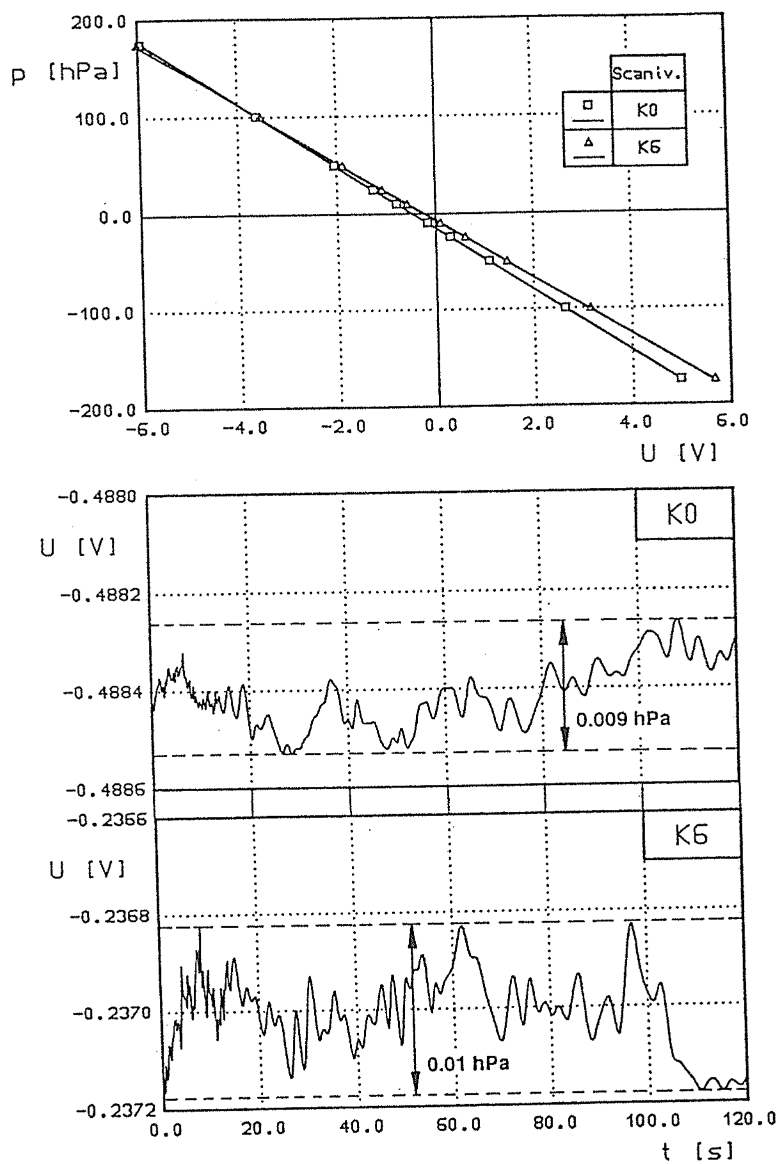


Fig. 3.9: Characteristics and zero offset drifts of two tested ±10 psid Scanivalve transducers

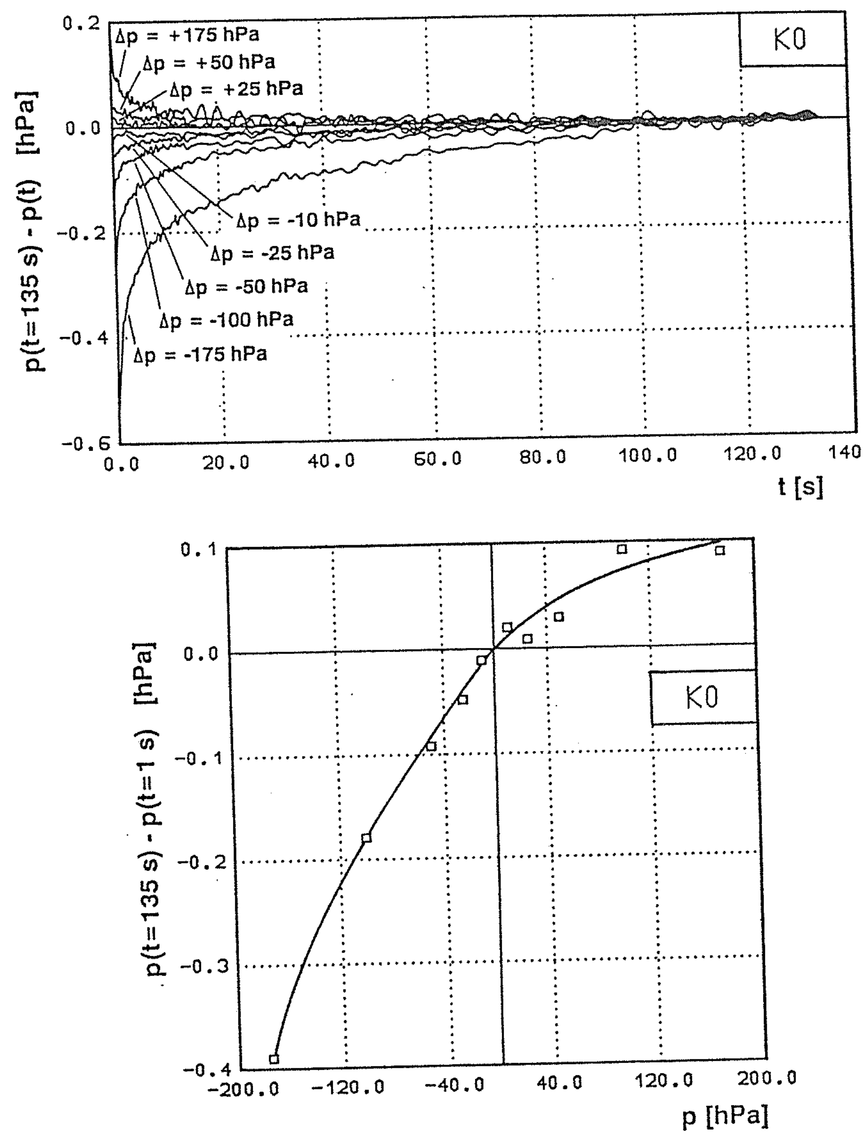


Fig. 3.10: Transient response of a ±10 psid Scanivalve transducer on a sudden change of pressure and measurement errors in cases of a scan rate of 1 reading/sec

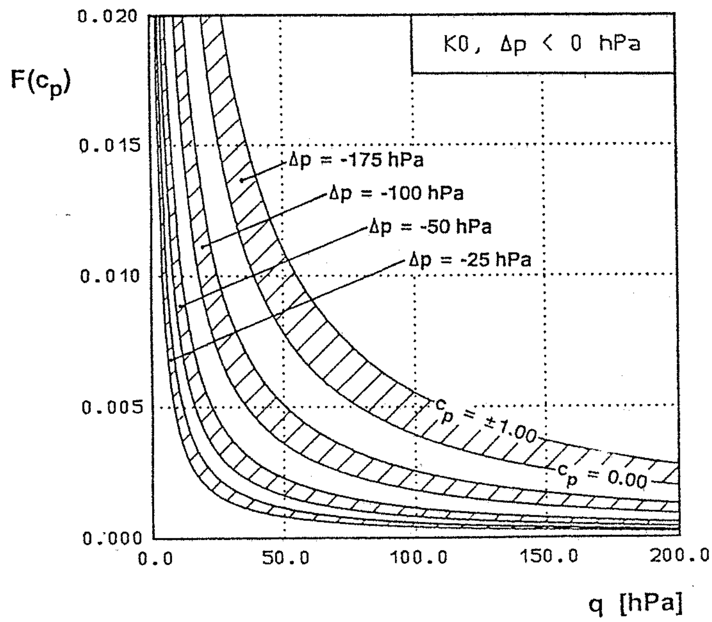


Fig. 3.11: Accuracy of the pressure distribution coefficient

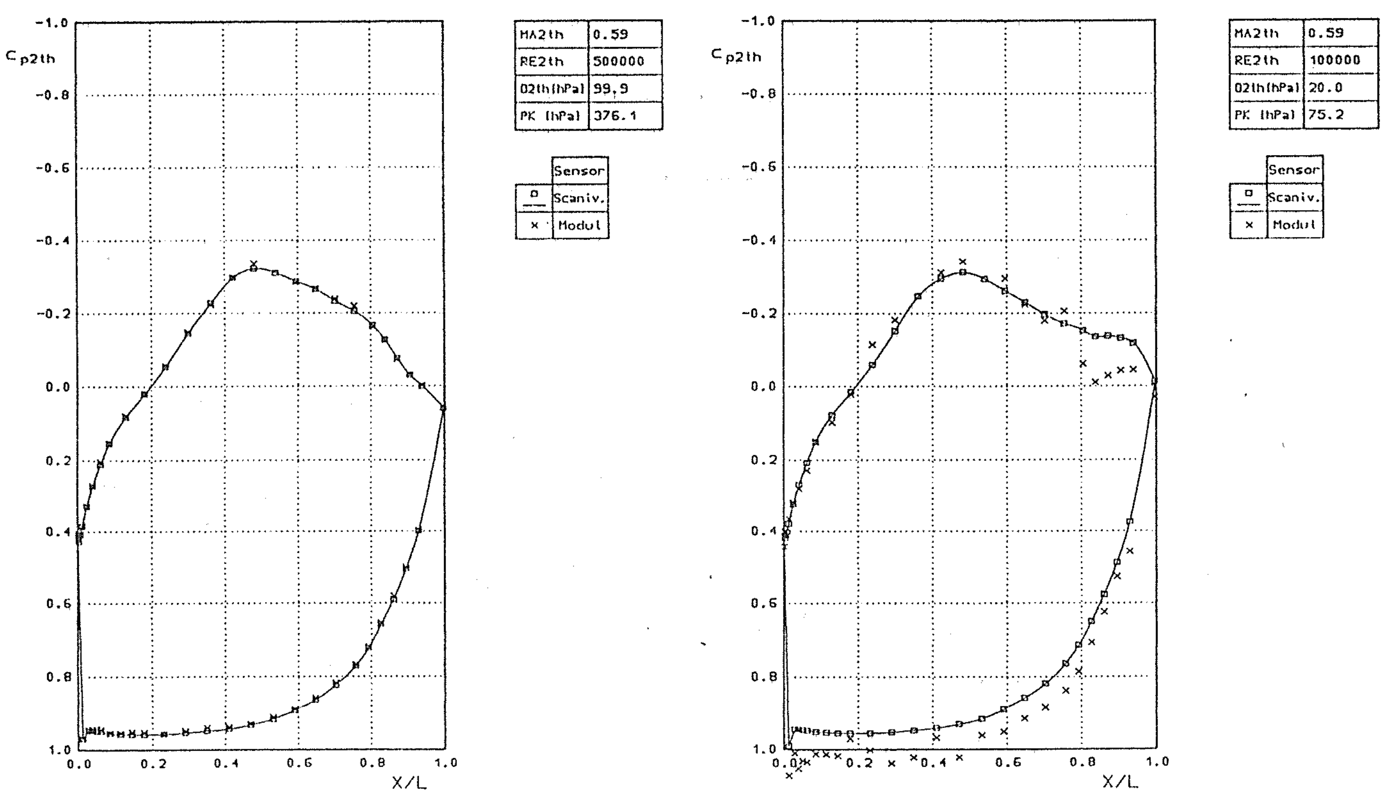


Fig. 3.12: Pressure distributions measured with Scanivalve tranceducers and simultaniously with multichannel transducer modules (see /9/)

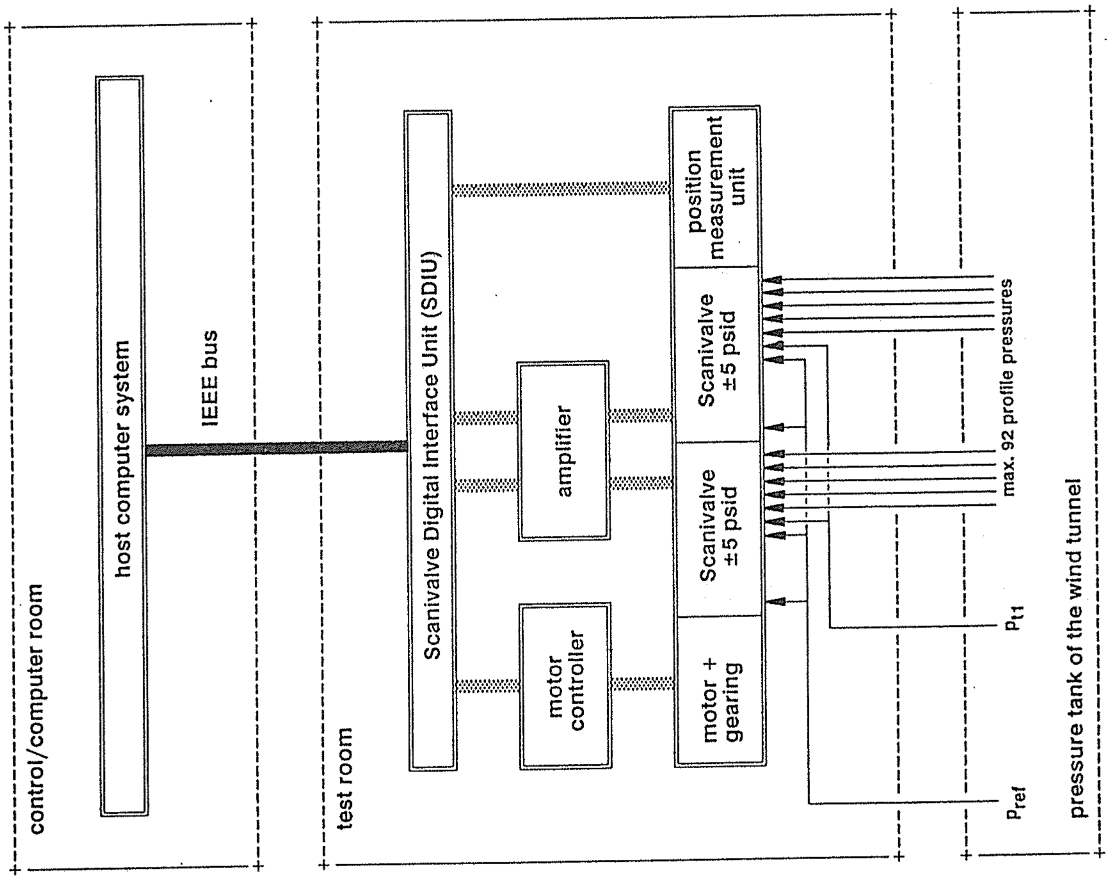


Fig. 3.13: Block diagram of the profile pressure measurement system

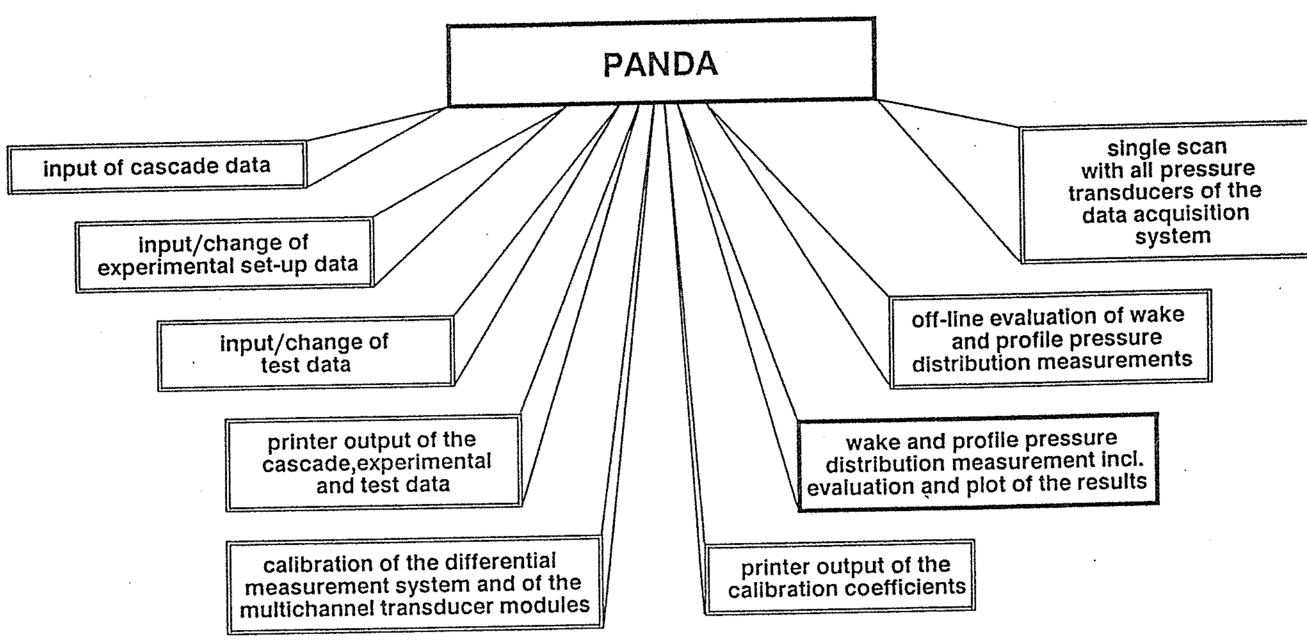
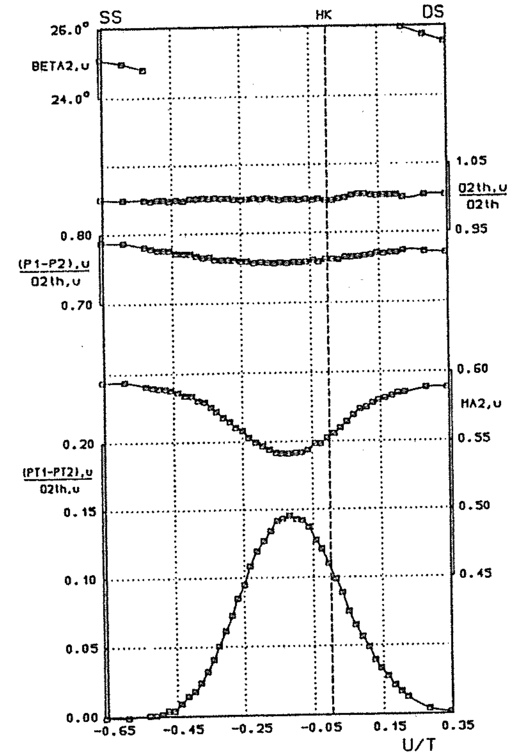
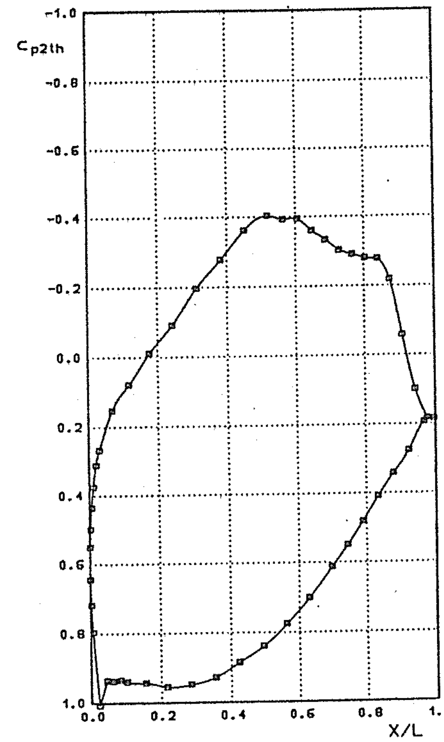


Fig. 3.14: Program modules of the software PANDA





BETA1	127.7°
MA2th	0.591
RE2th	149872
TU1 (%)	9.8
T/L	0.799
EM/L	0.4
Z (mm)	0.0
H/L	3.0
BETAS	60.7°
L (mm)	100.0
TT (C)	39.8
PT1 (hPa)	142.4
O2th(hPa)	30.0
OMEGA	1.0084
BETA2	25.3°
DPT/O2th	0.0519
DP/O2th	0.7674
MA1	0.261
MA2	0.572
CPkr	-1.240
U0/T	-1.057
V-Nr.	1829
Profil	T107

Fig. 3.15: Graphical display of the results provided by PANDA

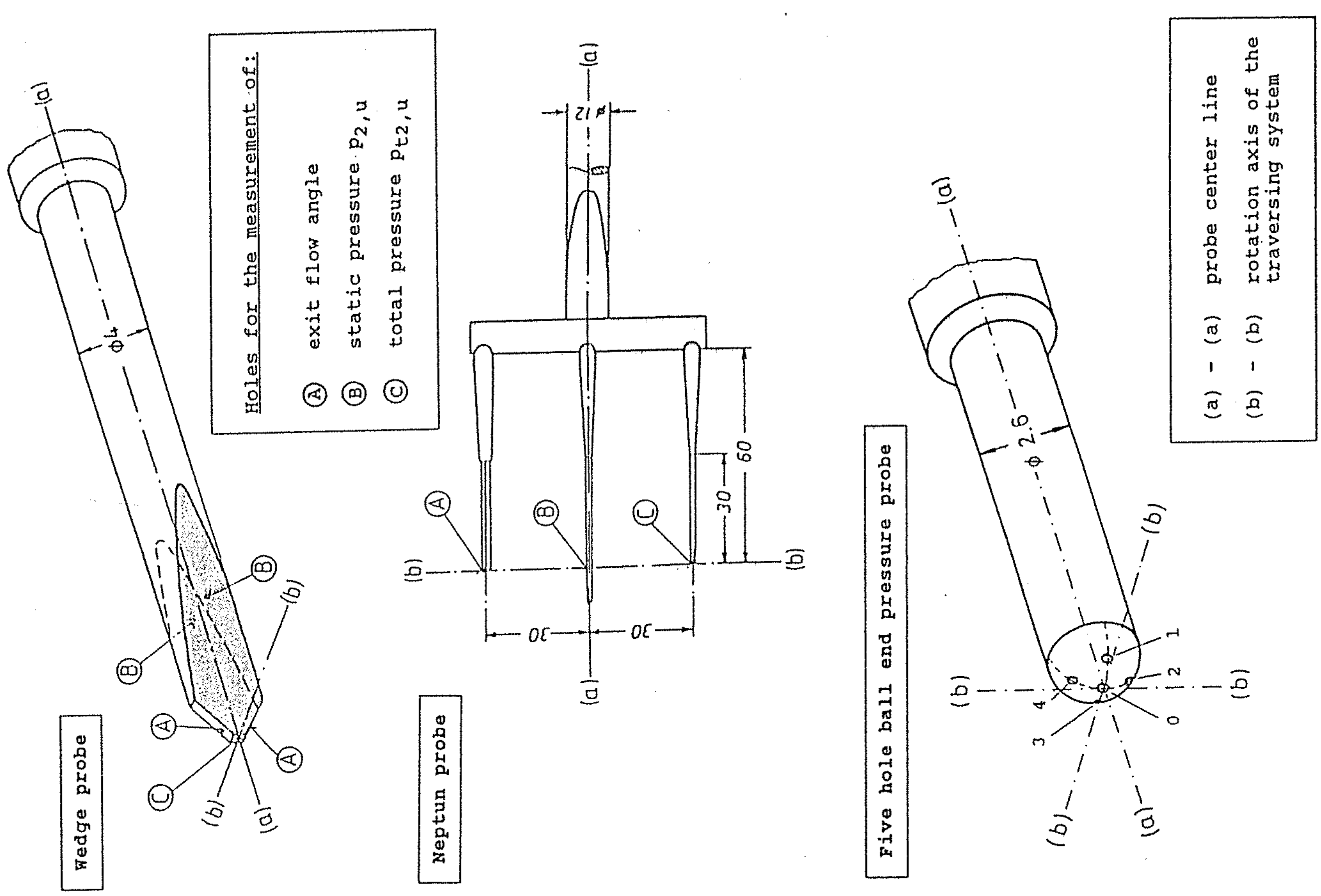


Fig. 4.1: Probes used for wake measurements

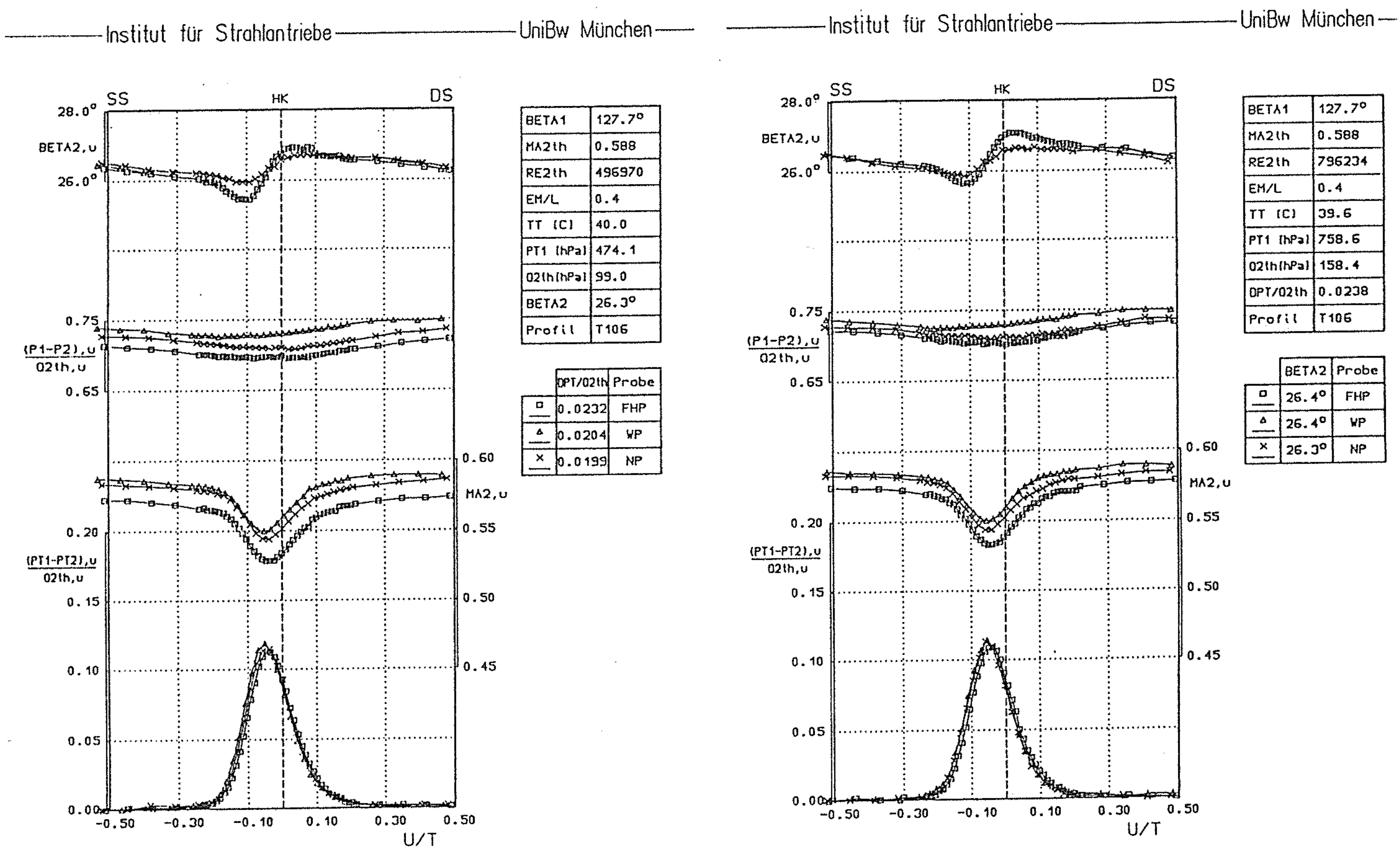


Fig. 4.2: Wake measurement results of a turbine cascade using different probes

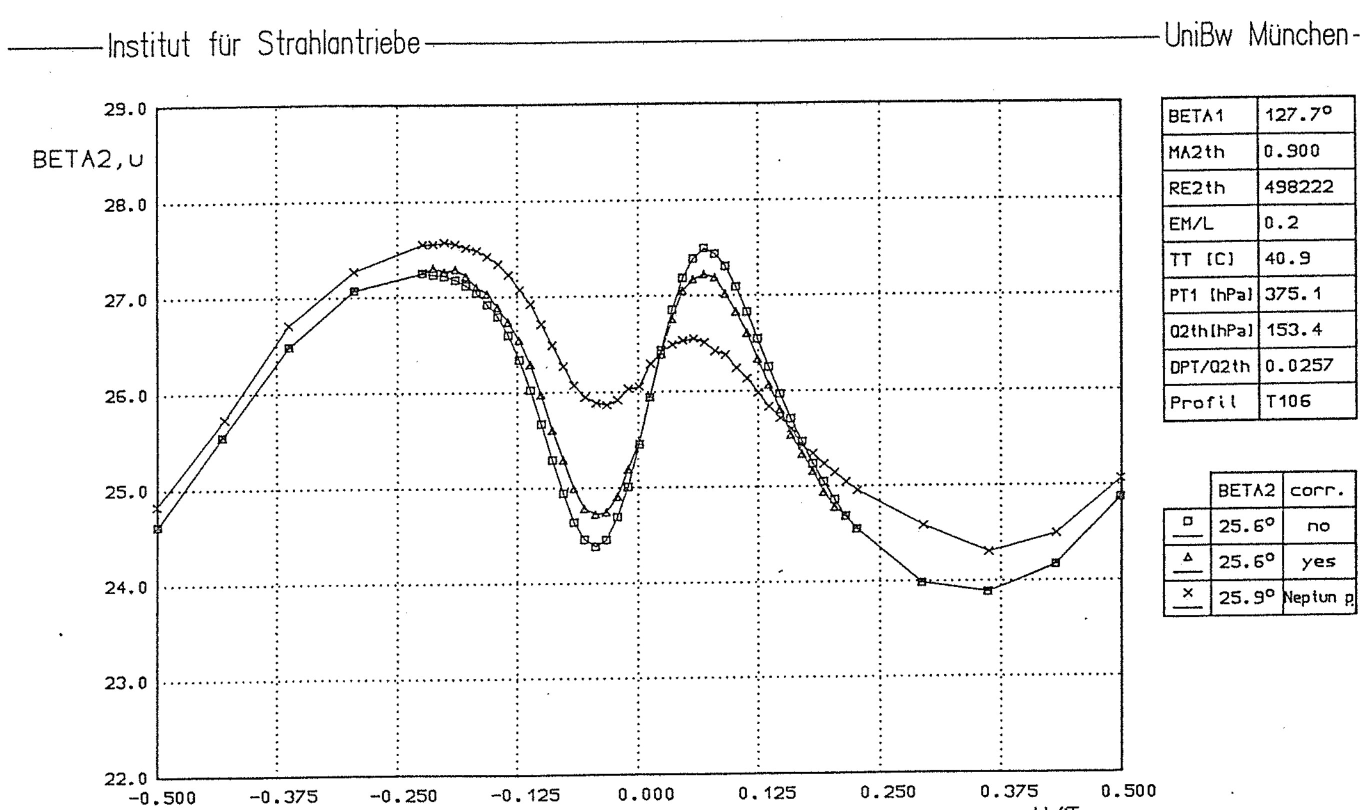


Fig. 4.3: Comparison of the exit flow angle measured with a five hole probe (uncorrected and corrected) and with a Neptun probe

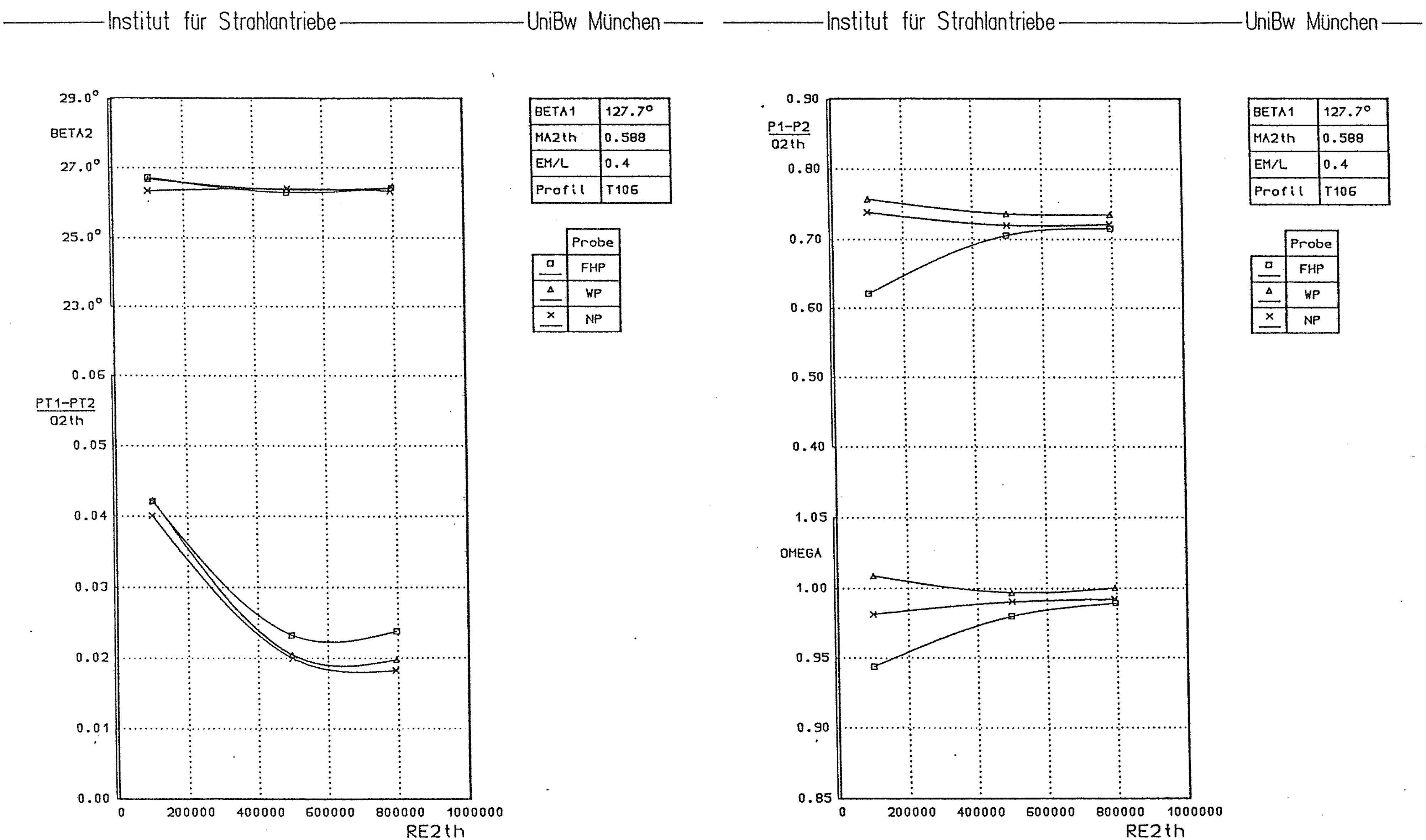


Fig. 4.4: Integral cascade parameters versus Reynoldsnumber for a turbine cascade determined with different wake probes