EXPERIMENTAL SETUP FOR DETAILED SECONDARY FLOW INVESTIGATION BY TWO-DIMENSIONAL MEASUREMENT OF TOTAL PRESSURE LOSS COEFFICIENTS IN COMPRESSOR CASCADES

Karsten Liesner, Robert Meyer

German Aerospace Center DLR
Institute of Propulsion Technology – Dept. of Engine Acoustics
Berlin, GERMANY

ABSTRACT

The department of Engine Acoustics of the German Aerospace Center in Berlin operates an especially designed high-speed subsonic cascade wind tunnel where secondary flow mechanisms in axial compressor flow are evaluated integrally. Instead of traversing a single 5-hole probe through the passage, a 26 + 5 - probe wake rake is used in order to minimise the measurement duration. Easy access to the test section and cascade blades allows surface flow visualization.

The long-term ambition of the experimental setup is to reduce total pressure losses resulting from corner separation. Passive and active flow control such as vortex generators or sidewall boundary layer aspiration is used. The test setup allows detailed investigation of the flow control effects. Total pressure loss coefficients are measured, the post-processing program is thereby able to rate active and passive secondary flow control mechanisms immediately. The gained data is recorded in a measurement computer. Due to a high degree of automation of the measurement string, the measuring period can be shortened to less than 10 minutes.

NOMENCLATURE

SYMBOLS

c	[mm]	chord
h	[mm]	height
p	[Pa]	pressure
u	[m]	peripheral coordinate
t	[mm]	blade pitch
w	[m/s]	absolute speed
z	[m]	blade height coordinate
Re	[-]	Reynolds number
Ma	[-]	Mach number
β	[°]	Flow Angle
ρ	[kg/m³]	density
ζ	[-]	total pressure loss coefficient

SUBSCRIPTS

1	conditions at inflow
2	conditions at outflow
g	global
m	mass-flow averaged
P	Profile/ Airfoil
W	Wall
BL	Boundary Layer
S	Secondary Flow

INTRODUCTION

Sidewall effects are responsible for a substantial amount of the total compressor losses of modern aero engines or stationary gas turbines. Current compressor blades with an aspect ratio of about c/h = 1 are characterized by a loss breakdown of 1/3 airfoil loss and 2/3 sidewall and secondary flow loss [1]. In order to minimize the losses produced by a blade stage, further understanding of secondary flow phenomena is essential. The main effort is to understand and reduce the secondary flow losses in a compressor stage. The test setup provides all kinds of passive and active flow control such as suction or blowing in the corner region. A fast mounting time ensures the possibility to regard the cascade with different settings and inflow conditions.

TEST SETUP

In order to investigate secondary losses in compressor cascades, a special experimental facility has been developed [2]. The high-speed subsonic wind tunnel allows Mach numbers of up to 0.7 and Reynolds numbers of up to 0.65×10^6 (formed with a 40mm chord length). A 65kW electric engine drives the radial-blow fan. The experimental setup provides a settling chamber with flow speeds of less than w = 1m/s. Here total pressure and total temperature are measured with only minor deviations. The flow accelerates to its final Mach number in the nozzle with a contraction ratio of 1:218. The adjacent rectangular test section with a cross section area of 40×82mm carries cascades with five stator blades. The test facility is shown in Fig. 1.

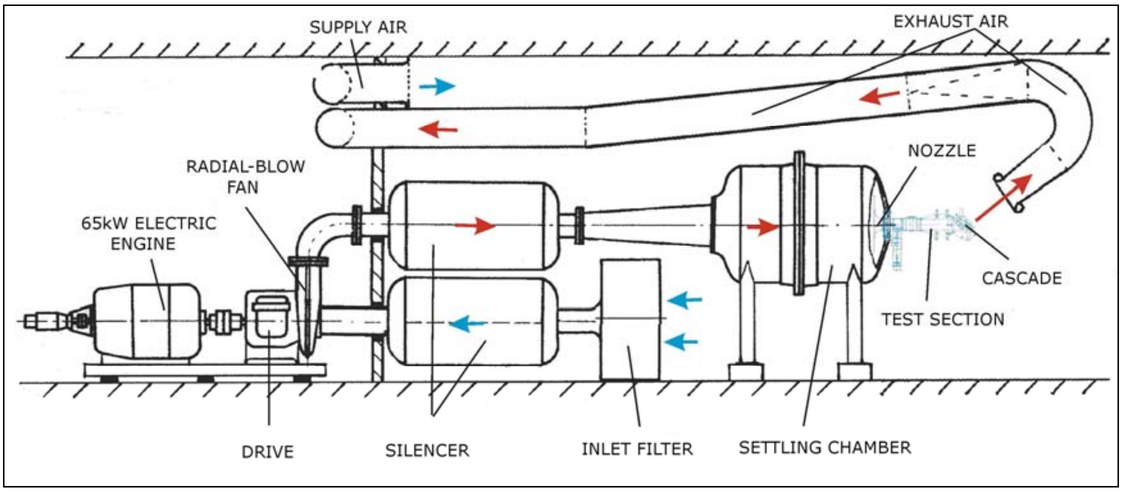


Fig. 1: Test Setup

BOUNDARY LAYER ASPIRATION

The rectangular test section provides boundary layer aspiration of all four tunnel side walls. By monitoring the static pressures along the cascade side walls with water columns and an independently adjustable aspiration rate of the upper and lower boundary layers, periodicity of the flow according to an “infinite blade cascade” is ensured. The sidewall boundary layer in the cascade inlet can be varied between 3 and 10mm. The length of the extendible inlet section varies boundary layer thickness between 4 and 10mm, by aspiration the thickness can be reduced by one mm. The boundary layer parameters are measured in a boundary layer rake upstream of the cascade.

CASCADE DESIGN

The cascades consist of 5 blades which are fixed at the sidewalls (Fig.2). Stagger angle correction is no longer required, as most airfoils are optimized for a fixed stagger angle. In order to alter the inlet angle β_1, the whole passage can be rotated over a wide range of angles. Determination of full working ranges of the compressor cascade is possible. Although the flow is regarded as infinite blade row flow, only the middle blade is investigated. Hereby the influence of the upper and lower channel side wall is minimised.

Active means of flow control can be implemented directly in the sidewalls. Blowing and suction slots and pressure connections can be integrated into the walls.

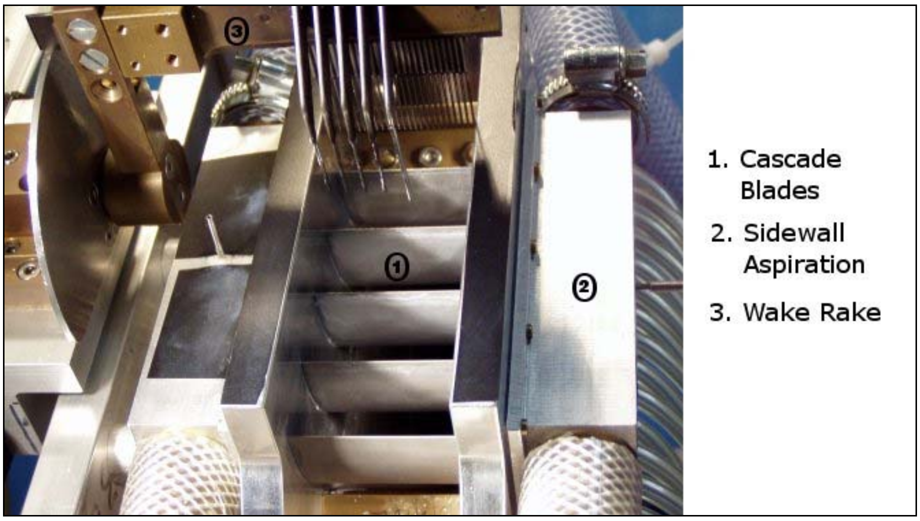


Fig. 2: Cascade with wake rake

DATA ACQUISITION

Most common for axial compressor cascade wind tunnels is the method of traversing a 5-hole probe through a passage. This method takes a long time as every measurement point is measured alone. In the method used here 26 points are measured simultaneously with one rake. The measurement plane is located 16mm (40%

chord length) downstream of the cascade outlet. The wake rake consists of two rows of probes (Fig. 3). The first row consists of 26 pitot tubes that are distributed over the vane height h from sidewall to sidewall. Herein the local total pressure for one position u/t=const can be determined simultaneously. The second row with an offset of one pitch length (t=22mm) consists of 4 Conrad angle probes and a static pressure probe. Conrad probes determine the angle of the downstream flow using a calibration equation [3]. The Conrad probes are distributed in one half span of the blades, symmetrical flow is assumed.

The wake rake is traversed in the circumferential direction u by a precision step-motor driving a jackscrew. As the traverse has a resolution of 100 steps per millimetre, the accuracy along the u-axis is very high.

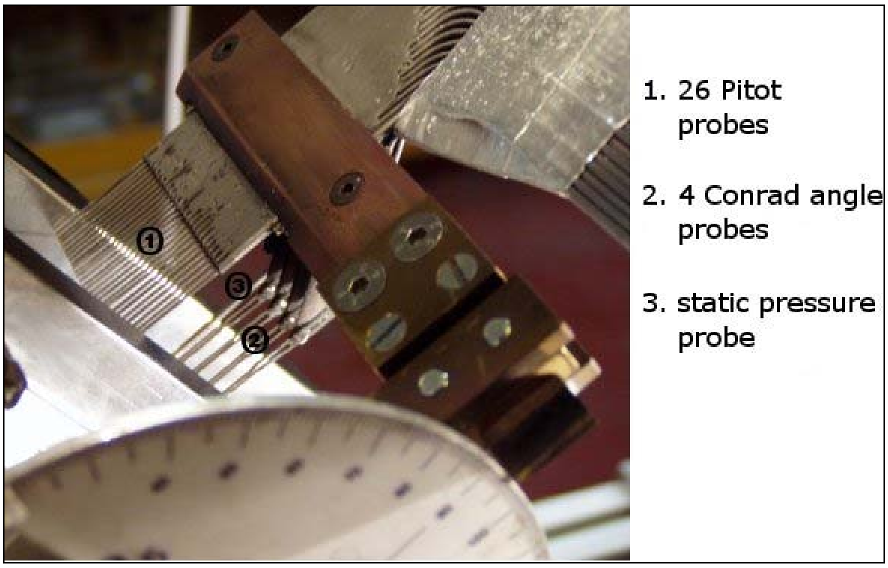


Fig. 3: Wake rake detail

PRESSURE TRANSDUCER

Since the measurement period is an important factor in experimental investigation, the test facility is equipped with a multi-channel pressure transducer for simultaneous recording of 48 pressure values. The Piezo-resistive sensors achieve an accuracy of ± 0.05 % (of full-scale). The pressure transducer system is delivered with an integrated Ethernet connection. The measurement string is automated; the whole measurement campaign for one configuration takes only 7-10 minutes.

All pressure data that is not subject to rapid changes as static and total pressure in the test chamber and settling chamber is measured by Baratron high precision pressure transducers. These achieve an accuracy of 0.05% (of measurement readings), regardless of the differential pressure level.

EXPERIMENTAL ACCURACY

The systematic uncertainty of the experimental setup according to DIN 1319 can be calculated. Therefore uncertainties of pressure and temperature measurement and their propagation have to be regarded. In the experimental setup, pressure transducers with a systematic measurement error of ± 0.05 % of full-scale and temperature sensors of the Pt100 type with a measurement error of ± 3K are used. A total uncertainty in measuring total pressure losses of ± 1.2 % can be derived. This uncertainty is the worst case, the errors can be minimised by a reasonable choice of pressure transducers´ range. Furthermore, the accuracy is raised by arithmetical averaging over a high number of pressure values. 20 - 50 single values are collected and averaged in the computer before usage in the post-process. By these means reproducibility with deviations of less than ± 0.2% is ensured.

MATHEMATICAL BACKGROUND

As it is unusual to speak of efficiencies in a stator stage or cascade, a local total pressure loss coefficient $\zeta(u,z)$ according to Andrews [4] is defined. It is calculated as follows:

$$\zeta(u,z)=\frac{p_{t1}-p_{t2(u,z)}}{q_1}=\frac{p_{t1}-p_{t2(u,z)}}{p_{t1}-p_1} \qquad 1)$$

Multiplied with the local mass-flow (formed with local density ρ and absolute velocity *w*) and divided by the integral mass flow, a mass-flow-averaged loss coefficient $\zeta_m(u,z)$ [5] is defined. The coordinate definition is shown in Fig. 4.

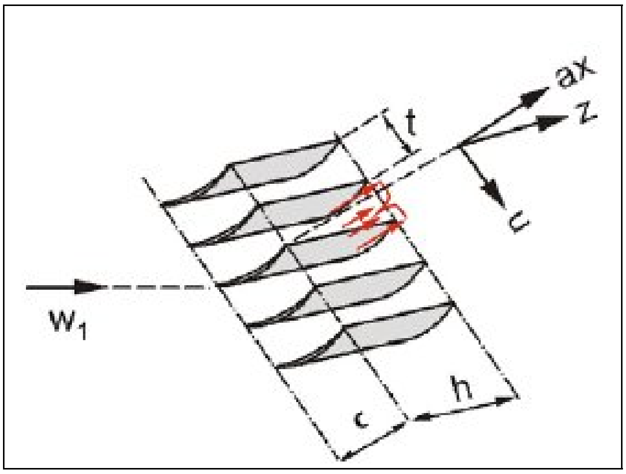


Fig. 4: Cascade coordinates

$$\zeta_m(u,z) = \frac{\zeta(u,z) * \rho(u,z) * w(u,z) * du * dz}{\int\limits_{u=0}^{u=t} \int\limits_{z=0}^{z=h} \rho(u,z) * w(u,z) * dz * du} \qquad 2)$$

Integrated along the passage, the mass-flow-averaged local total loss coefficients form a global total loss coefficient ζ_g:

$$\zeta_g = \int\limits_{u=0}^{u=t} \int\limits_{z=0}^{z=h} \zeta_m(u,z) \qquad 3)$$

LOSS BREAKDOWN

Losses in axial turbo machines are classified according to their cause [6]. In compressor cascades it is distinguished between airfoil losses (ζ_P) and sidewall losses (ζ_W), whereas the latter are subdivided into inlet boundary layer losses (ζ_{BL}) and secondary flow losses (ζ_S). Airfoil losses by definition are the amount of losses in the half span of the blade (Fig. 5). The inlet boundary layer losses can be calculated using the boundary layer probes upstream of the cascade. The secondary flow losses are hence easily determined.

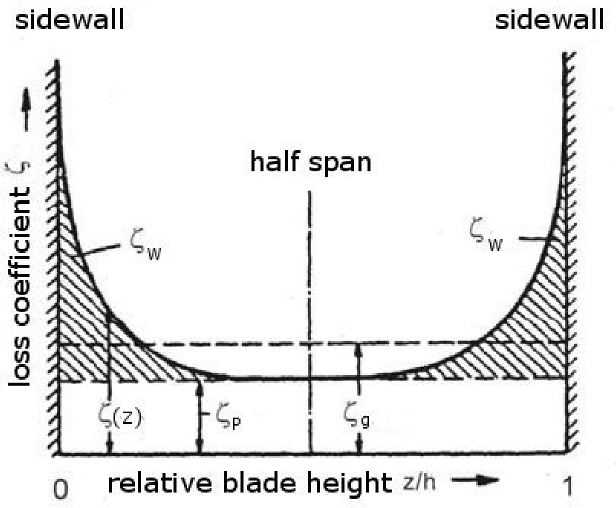


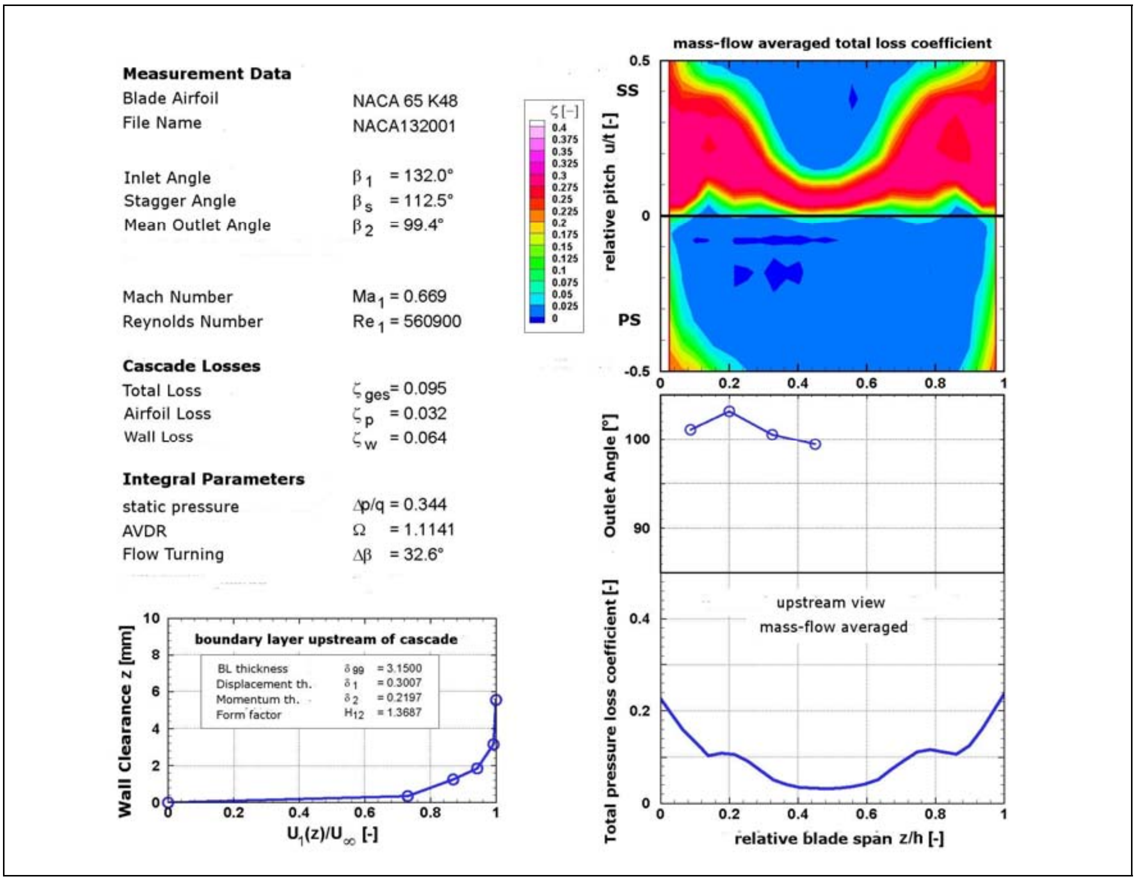
Fig. 5: Loss breakdown

$$\zeta_g = \zeta_P + \zeta_W = \zeta_P + \zeta_{BL} + \zeta_S \qquad 4)$$

DATA INTERPRETATION

All measured data is collected in a processing computer. A program developed in the department of Engine Acoustics of the DLR is used for post-processing of the measurement data, which automatically generates output files for further consideration. A graphical layout file is created, in which wake characteristics can be observed.

All measured factors and coefficients of interest are shown in the output graphic Fig. 6. The losses, distinguished between profile and secondary losses can be read next to Mach and Reynolds number. A boundary layer profile is shown as well. The 2D graphic in the lower right corner shows the integral flow outlet angle and the integral averaged total pressure loss coefficient in span wise direction.



Measurement Data
Blade Airfoil NACA 65 K48
File Name NACA132001

Inlet Angle β_1 = 132.0°
Stagger Angle β_s = 112.5°
Mean Outlet Angle β_2 = 99.4°

Mach Number Ma_1 = 0.669
Reynolds Number Re_1 = 560900

Cascade Losses
Total Loss ζ_{ges} = 0.095
Airfoil Loss ζ_p = 0.032
Wall Loss ζ_w = 0.064

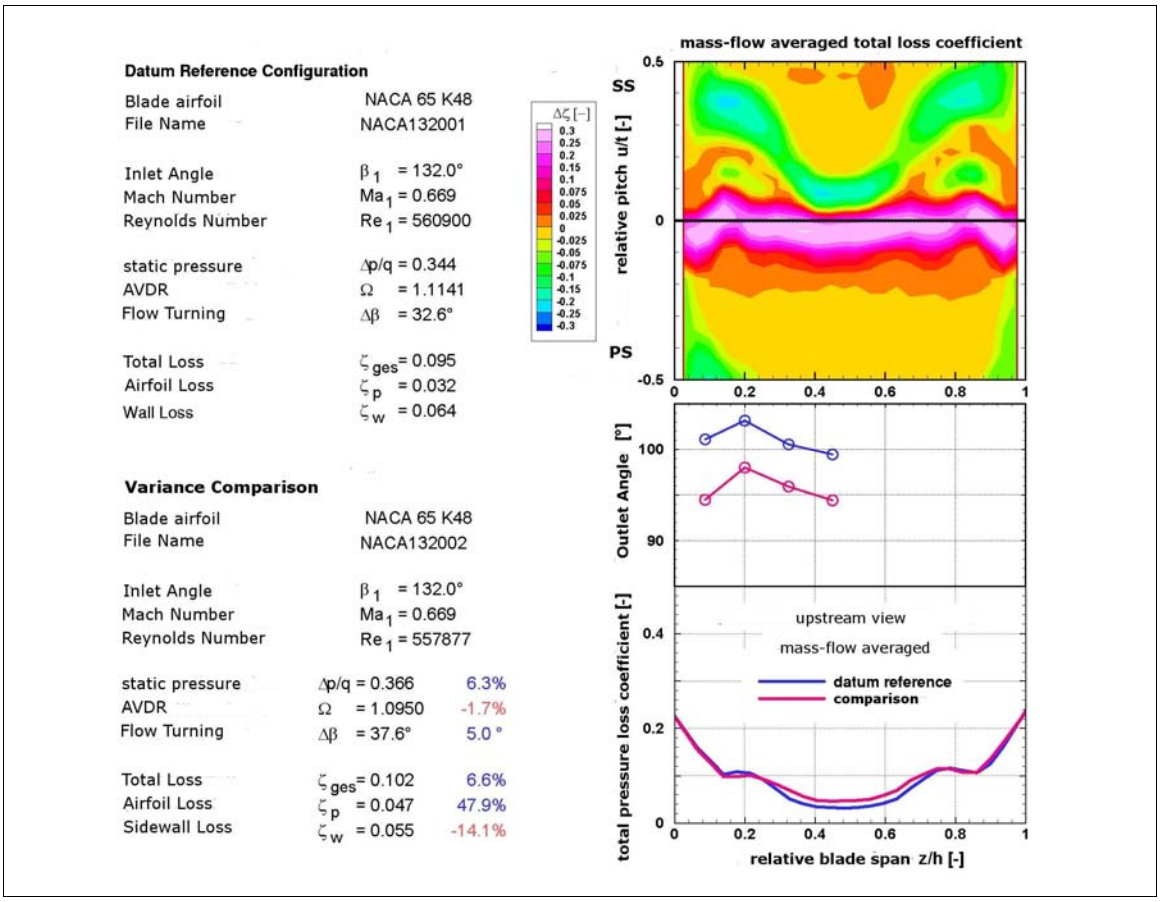
Integral Parameters
static pressure $\Delta p/q$ = 0.344
AVDR Ω = 1.1141
Flow Turning $\Delta\beta$ = 32.6°

boundary layer upstream of cascade
BL thickness δ_{99} = 3.1500
Displacement th. δ_1 = 0.3007
Momentum th. δ_2 = 0.2197
Form factor H_{12} = 1.3687

Fig. 6: Graphic output of measurement results

The most significant part of the post processing graphic is the coloured 2D plot of the mass flow averaged total pressure loss coefficients. Vortices and separated flow are identifiable on the first view.

In measurement campaigns where a known datum reference configuration is to be compared with new data, a subprogram is available to directly compare loss values and pressure distribution in one output file (Fig. 7). Instead of total loss coefficients, the contour plot shows differences in the loss coefficient distribution in the positive or negative direction. All output files are standardised and allow easy comparison between two measurements.



Datum Reference Configuration

Blade airfoil	NACA 65 K48
File Name	NACA132001
Inlet Angle	β_1 = 132.0°
Mach Number	Ma_1 = 0.669
Reynolds Number	Re_1 = 560900
static pressure	$\Delta p/q$ = 0.344
AVDR	Ω = 1.1141
Flow Turning	$\Delta\beta$ = 32.6°
Total Loss	ζ_{ges} = 0.095
Airfoil Loss	ζ_p = 0.032
Wall Loss	ζ_w = 0.064

Variance Comparison

Blade airfoil	NACA 65 K48	
File Name	NACA132002	
Inlet Angle	β_1 = 132.0°	
Mach Number	Ma_1 = 0.669	
Reynolds Number	Re_1 = 557877	
static pressure	$\Delta p/q$ = 0.366	6.3%
AVDR	Ω = 1.0950	-1.7%
Flow Turning	$\Delta\beta$ = 37.6°	5.0 °
Total Loss	ζ_{ges} = 0.102	6.6%
Airfoil Loss	ζ_p = 0.047	47.9%
Sidewall Loss	ζ_w = 0.055	-14.1%

Fig. 7: Graphic comparison output of two measurement results

SUMMARY

The subsonic cascade wind tunnel provides the opportunity to instantly measure the effectiveness of secondary flow control with deviations in reproducibility of less than 0.2%. In a time span of 7-10 minutes an automated measurement is performed by which losses in the whole passage can be determined and viewed graphically. Secondary flow appearance and resulting losses can be evaluated in detail. Conclusions concerning secondary flow control effectiveness can be derived instantly from the experimental investigation. Standardised output files allow easy comparison between different measurements.

REFERENCES

[1] Watzlawik, R.: “Untersuchung der wesentlichen Einflußfaktoren auf die Sekundaerverluste in Verdichter- und Turbinengittern bei Variation des Schaufelseitenverhaeltnisses”, Ph.D. Thesis, Fakultaet für Luft- und Raumfahrt der Universitaet der Bundeswehr Muenchen (1991)

[2] Meyer, R.: “Versuchsaufbau und Auswerteverfahren für ebene Verdichtergitter mit Sekundaerstroemungsbeeinflussung bei hohen Unterschall-Geschwindigkeiten”, DLR-IB-92517-02 (2002)

[3] Nitsche, W.: “Stroemungsmesstechnik”; Springer-Verlag Berlin Heidelberg New York (1994)

[4] Andrews, S.J.: “Tests related to the Effect of Profile Shape and Camber-Line on Compressor Cascade Performance”, ARC Technical Report, R&M No. 2743 (1949)

[5] Meyer, R.: “Massenstromgemitteltes Auswerteverfahren für ebene Verdichtergitter mit Sekundaerstroemungsbeeinflussung bei hohen Unterschall-Geschwindigkeiten”, DLR-IB-92517-05 (2005)

[6] Scholz, N.: “Ueber den Einfluss der Schaufelhoehe auf die Randverluste in Schaufelgittern”; DK 533.6.013.12:621-135; Rundschau Forschung 20. Band/Heft5 , DF457, 1954