Paper 4

12th Symposium on Measuring Techniques
for Transonic and Supersonic Flow in Cascades and Turbomachines

Prague, Czech Republic, September 12-13,1994

SCHLIEREN METHOD WITH QUANTITATIVE EVALUATION BY DIGITAL IMAGE PROCESSING

R.M. Bell, L. Fottner
Universitat der Bundeswehr Munchen
Germany

Schlieren Method with Quantitative Evaluation by Digital Image Processing

Ralf M. Bell and Leonhard Fottner
Institut für Strahlantriebe
Universität der Bundeswehr München
85577 Neubiberg
Germany

ABSTRACT

In order to obtain quantitative information of the shock/boundary-layer interaction in a transonic cascade flow a schlieren method was supplemented with digital image processing. A detailed description of the image processing is given, as well as the calibration procedure to obtain the quantitative density gradients. As a result, the quantitative evaluations of the schlieren pictures lead to the density field of the transonic flow field. Influence factors and measurement errors are discussed. A comparison between a quantitative schlieren image and laser velocimetry measurements is given for a transonic compressor cascade flow showing good agreement.

NOMENCLATURE

Symbols:

A	[m^2]	area of passing light source image
D	[m]	diameter of aperture
F	[m]	focal length of schlieren head
g_p	[-]	gray level of pixel
G	[m^3/kg]	Gladestone-Dale constant
h	[m]	area height of passing light source image
H	[m]	test section width
I	[lux]	light intensity
Ma	[-]	Mach number
n	[-]	refractive index
x, y, z	[m]	cartesian coordinates
ε	[°]	deflection angle
ρ	[kg/m^3]	density

Indices:

0	quantity without deflection
is	isentropic quantity
m	averaged quantity
sk	quantity at schlieren knife edge

INTRODUCTION

The schlieren method belongs to the standard optical measurement techniques in transonic and supersonic cascade flows. In these flows shock waves occur and their interactions with the blade boundary-layers may alter the shock structures (e.g. Schreiber and Starken, 1991). The calculation of such flow phenomena, especially loss and deviation predictions, are still inaccurate because of the unresolved interaction process.

Here, schlieren pictures give a very good impression of shock structures and shock/boundary-layer interactions. But in conjunction with the evaluation of physical quantities they possess a much higher value for flow analysis and numerical code validation.

This paper describes a standard schlieren method supplemented with a digital image processing which was assembled at the High-Speed Cascade Wind Tunnel of the Federal Armed Forces University, Munich (Sturm and Fottner, 1985). Emphasis is given to the image processing method and the suggested calibration procedure to obtain the physical quantities. A discussion of influence factors and some experimental results are included in this paper.

DESCRIPTION OF THE SCHLIEREN METHOD

In transonic and supersonic flows shock-waves and compressible boundary-layers are always present causing high density gradients and changes of refractive indices. These density gradients can be visualized by deflected light beams transmitted through the flow field as it is used by the schlieren method.

The schlieren method in use at the High-Speed Cascade Wind Tunnel is based on the standard "Toepler apparatus" with a schlieren knife edge in the focal plane of the schlieren head. A detailed description of the Toepler method can be found in Schardin (1934) or Merzkirch (1987). The optical setup as shown in Fig. 1 is done in a two-mirror Z-configuration with achromats to minimize optical errors like coma (Domann, 1988). A Xenon high pressure lamp is used as a light source followed by a circular aperture with variable diameter. The rotatable and movable schlieren knife edge is positioned in the focal plane of the schlieren head. Astigmatism is corrected by using a vertical knife edge in the tangential focal plane and a horizontal knife edge in the sagittal focal plane. The flow information is recorded by a CCD camera positioned in the image plane of the test section. In front of the camera some neutral filters are installed in order to reduce the enormous light intensity of the light source.

DETERMINATION OF DENSITY GRADIENTS AND DENSITY FIELD

With the schlieren technique in use parallel light beams are transmitted perpendicular through the flow field. These light beams are deflected at locations with changing refractive indices causing a shift of the light source image in the focal plane (see Fig. 2). The shift Δh is a function of the deflection angle ε and the focal length of the schlieren head F. (The following equations are given for vertical shifts perpendicular to the horizontal knife edge.)

$$\tan \varepsilon_y = \frac{\Delta h_y}{F} \qquad (1)$$

Furthermore, there is a relation between the deflection angle and the refractive index n given by

$$\tan \varepsilon_y = \int_0^H \frac{1}{n} \cdot \frac{\partial n}{\partial y} \, dz \qquad (2)$$

for small deflections (see Merzkirch 1987). z points in the direction of the light beams and H is the test section width. Another important relation is the Gladestone-Dale equation describing the refractive index as a function of the density ρ:

$$n - 1 = G \cdot \rho \qquad (3)$$

G is the Gladestone-Dale constant and depends on the flow medium and the wave length of the light source (here: $G=2.27 \cdot 10^{-4}$ m^3/kg). Assuming a constant gradient of the refractive index along the test section width the following equation is found for the density gradient in one direction:

$$\frac{\partial \rho}{\partial y} = \frac{1 + G \cdot \rho}{H \cdot G \cdot F} \cdot \Delta h_y \qquad (4)$$

The assumption of a constant gradient of the refractive index is only justified for two-dimensional flows or quasi two-dimensional flows. But that can be proved with the aid of oil flow visualizations or three-dimensional viscous calculations. Otherwise, only an integral density gradient is obtained.

Since the term $G \cdot \rho$ of equation (4) is of a very low order (here: $G \cdot \rho \approx 10^{-5}$), the factor $\left((1+G\cdot\rho)/(H\cdot G\cdot F)\right)$ does not depend significantly on the density and can be substituted by a constant k so that

$$\frac{\partial \rho}{\partial y} = k \cdot \Delta h_y \qquad (5)$$

After determining the density gradients in both directions it is possiple to obtain the density field of the whole flow field by the following integration procedure:

$$\rho(x,y) = \rho_{ref} + \int_{x_{ref}}^{x} \frac{\partial \rho}{\partial x}\,dx + \int_{y_{ref}}^{y} \frac{\partial \rho}{\partial y}\,dy \qquad (6)$$

The density ρ_{ref} at the point with the coordinates (x_{ref}, y_{ref}) may be given for the inlet flow or may be calculated from known total quantities of the inlet flow and a measured wall pressure. Other quantities like the pressure field or Mach number distributions may be evaluated with the aid of the gasdynamic relations assuming an isentropic flow.

In order to obtain the quantitative density gradient from equation (5) the shift in the focal plane must be measured. Using the schlieren method it is known that a shift in the focal plane causes a change of the light intensity in the recording plane. Consequently, the quantitative density gradient can be determined indirectly by measuring the change of the light intensity in the recording plane. This can be done with a CCD camera as a part of a digital image processing system.

SYSTEM OF DIGITAL IMAGE PROCESSING

Using digital image processing a high geometrical and aerodynamical resolution is obtained as a result of the conversion of the analogous flow information into digital data. The geometrical digitization is done by dividing the image with the flow information into a certain number of rows containing many picture elements (pixels). Each pixel provides a certain information of light intensity representing an aerodynamical value.

The digital image processing system is based on a powerful personal computer with a frame grabber as it is suggested by Schnerr (1988). It consists of the following components (Fig. 3):

- CCD camera
- video recorder
- personal computer including a frame grabber
- monitors for system and grabbed images
- video printer

The measurement of the local light intensity is done by a CCD camera chip doing also a first geometrical digitization. Each picture element of the CCD chip collects a certain amount of charge depending on the incoming light intensity and the exposure. After the exposure the charges of all pixels in a row are converted into a voltage signal. The complete image signal at the output of the CCD camera includes the voltage signals of each row and is setup for the CCIR standard. The CCIR standard gives 25 images per second with 625 image rows for one image. A very important feature of the CCD camera used is a variable exposure time with a lowest value of 10^{-4} s.

The next step in the image processing is storing the images on a video tape or grabbing the images with a frame grabber being part of the personal computer. Here, in case of the frame grabber, a second geometrical digitization takes place and each pixel gets certain coordinates (row and column number) with a value called gray level according to the voltage height. This is done by an A/D converter operating with an adjustable frequency for the resolution of the voltage signal of each image row. Moreover, the A/D converter has a fixed digitization possibility for the voltage height of each pixel. After the digitization process the image is transmitted to a frame buffer memory representing the central unit of the frame grabber. The processor of the computer has a direct access to the memory in order to store or manipulate the image informations. The output unit of the frame grabber transmits the image informations from the frame buffer memory to the image monitor and provides the possibility of pseudo colouring the images by look-up-tables. For documentation purposes, a video printer is connected to the frame grabber output.

The image processing is controlled by a commercial software called "Image-Pro PLUS" by MEDIA CYBERNETICS. This is a very powerful software tool due to the possibilities for many digital image processings like image handling, analysis, filter operations etc.

GEOMETRICAL AND AERODYNAMICAL RESOLUTIONS

The geometrical resolution depends on three factors. First, the analogous image information is divided into a digital grid with a certain number of active picture elements on the CCD camera chip. Second, the way of transmitting the image from the camera to the frame grabber may alter the resolution. Third, the last digitization process with the frame grabber divides the image into a digital grid with adjustable numbers of rows and columns representing a bitmap. Here, a schlieren window with 90 mm height and 110 mm width has been resolved with 768*576 pixels giving 6 pixels per mm.

The aerodynamical resolution depends on the digitization process of the frame grabber with its gray levels between dark and bright. The frame grabber in use operates with an 8 bit resolution per pixel for the light intensity, or 255 gray levels. With this resolution a light intensity change of 0.4% can be detected. Furthermore, with respect to equations (1) and (5) the maximum density gradient depends on a maximum detectable shift which is a function of the focal length of the schlieren head, the diameter of light source image, and the position of the schlieren knife edge. For the purpose of detecting density gradients in both directions with equal order and a light source diameter of 4 mm the maximum density gradient is about 20 kg/m^4 and the minimum density gradient is 0.16 kg/m^4 (F=1492 mm).

CALIBRATION PROCEDURE

For the purpose of determining quantitative density gradients a relation between the shift Δh and the light intensity change ΔI is needed. According to Merzkirch (1987) the dependency can be expressed by

$$\frac{\Delta I}{I_0} = \frac{\Delta A}{A_0} \tag{7}$$

where A is the area of the light source image passing the schlieren knife edge. Moreover, this area is a function of area height h (Index 0 describes the situation in the absence of any disturbance in the test section.). Using equation (7) an almost perfect optical setup should be given which could not be obtained during the test phases. Especially, there are a lot of influence factors on the light intensity in the recording plane which are discussed in the next chapter.

Another calibration procedure was proposed by Schardin (1934) who used a plane convex lens with known deflections at any point on the lens. As a result of image analysis with such a lens, a relation is found between light intensity and deflection angle which can be used for determining the density gradient. This can also be done with a wedge type glass which should be rotatable to provide different light beam deflections. A test with a plane convex lens led to an unacceptable light intensity absorption of 30%. In addition, an adjusting device with an accuracy of 0.001° was not available.

At last, a calibration procedure was used where a shift due to a deflection angle is simulated (Fig. 4). The simulation can be done by an active change of schlieren knife edge position providing a change of light intensity in the recording plane. Thus, a relation between light intensity expressed with an averaged gray level and area height can be described as it is shown in Fig. 5 for a horizontal and vertical schlieren knife edge. The calibration curves show a sinusoidal trace which is due to a sine-shaped change of passing area in case of a circular light source. Also, the curves are not identical which is mainly affected by the optical error astigmatism. It should be noted that the proposed calibration procedure assumes that additional shifts as a result of refraction at glass windows in the test section are negligible.

INFLUENCE FACTORS AND MEASUREMENT ERRORS

With the quantitative schlieren method described all local changes of light intensity are evaluated to calculate the density gradients. But, not all changes are induced by the flow itself and that is due to a lot of influence factors. These influence factors can be grouped in local and global parameters. The local parameters influence the light intensity of a specific part of the image as a result of unsteady effects and non-uniform illumination. Unsteady heat waves emanating from the light source or being produced out of the test section and vibrations belong to local influence factors. Furthermore, the non-uniform illumination is a result of diffraction at edges or surface waves and pollution at glass windows. The global light intensity, determining the brightness of the whole image, is influenced by the light source power and aperture size, the number of glass windows and filters, and the exposure time of the camera. The measurement errors are mainly affected by local parameters causing a non-uniform illumination of the image.

In order to illustrate some influence factors an analysis of a schlieren image without flow velocity is presented in Fig. 6. The gray level profile of any chosen line shows high and low frequency structures. The low frequency changes are due to surface waves of the glass windows, heat waves of the light source, and diffraction especially at the light source aperture. Pollution and noise due to the digitization process cause high frequency structures. On account of the non-uniform illumination the image shown is characterized by an averaged gray value of 159 with a standard deviation of 14. The standard deviation should be small because only a mean gray value is used for the calibration curves.

An estimation of measurement errors has been done with the comparison of two images grabbed at different times. Here, only unsteady effects such as heat waves of the light source influence the local light intensity. Fig. 7 shows the differences in gray values of the two images and the relative errors with respect to a maximum gray level. Almost all gray value differences are smaller than 4, but differences of 10 can appear. These gray level differences lead to relative errors smaller than 5%. These measurement errors seem to be high especially for flow regions with low density gradients, but during the test phases they could not be avoided. A different light source may reduce the measurement errors significantly.

EXPERIMENTAL RESULTS

The schlieren method with digital image processing has been applied to the investigation of the shock/boundary-layer interaction in a highly loaded compressor cascade. An example of a strong shock/boundary-layer interaction shows Fig. 8. The schlieren pictures show a strong passage shock-wave causing boundary-layer separation on the blade suction surface. It should be noted that the interaction process is not steady and shock oszillation over a length of 20% chord can occur. Therefore, the schlieren pictures represent only instantaneous flow situations.

The resulting quantitative schlieren image is shown in Fig. 9 in comparison with laser two-focus velocimetry measurements in the mid span of the compressor cascade (Beeck, 1992). The isentropic Mach number has been evaluated from the density field of the schlieren image and the local Mach number is shown for the laser measurements. The Mach number distributions in front of the shock-wave have a very special structure which is caused by the interaction of the shock-wave with a laminar boundary-layer. Here, the upstream pressure diffusion inside the boundary-layer plays a dominant role and leads to a precompression in front of the shock-wave near to the suction side. The agreement with the laser measurements is quite good and differences in Mach number distributions are due to the averaged measurement values of the applied laser technique. In addition, three dimensional effects caused by side wall boundary-layers may bring about discrepancies. However, the main important objectives are resolutions and measuring times. The quantitative schlieren image has a resolution of more than 400000 pixels including the boundary-layer compared with 110 laser measurement points only in the main passage flow. Schlieren image grabbing and evaluation on a workstation takes 15 minutes compared with three hours laser field measurements.

The next figure (Fig. 10) shows the quantitative density gradients and the calculated density field in the region of shock/boundary-layer interaction. The compressible boundary-layer in front of the shock-wave is marked by high density gradients normal to the flow direction. In addition, in the shock foot region a superposition takes place with the density gradients of the shock-wave.

CONCLUSIONS

A standard schlieren method with quantitative evaluation by digital image processing is described which has been successfully established at the High-Speed Cascade Wind Tunnel of the Federal Armed Forces University, Munich. The system configuration based on a personal computer is described and a calibration procedure to obtain the quantitative density gradients is proposed.

The schlieren method with digital image processing provides a fast availability of schlieren pictures which can also be corrected qualitatively in an easy way. Also, the schlieren pictures are available in a digital format with a high resolution for the use of numerical calculations.

A comparison between laser velocimetry measurements and quantitatively evaluated schlieren pictures shows good agreement for a transonic cascade flow being quasi two-dimensional. But, further improvement of the optical setup is still required especially in order to reduce the measurement errors mainly caused by the light source of the schlieren method. Moreover, simultaneous grabbing of images with vertical and horizontal schlieren knife edges may be a useful extension to take better care of unsteady flow phenomena.

To sum up, with the schlieren method described a powerful tool is given to obtain a lot of information with high resolution in a very short time. This may be very useful for high-speed flow analysis and numerical code validations. In addition, the digital image processing based on a personal computer is a low-cost measuring technique compared with a laser velocimetry or a hot-film anemometry.

ACKNOWLEDGMENT

This research project has been supported by Deutsche Forschungsgemeinschaft (DFG Fo 136/3). The support and the permission for publication is gratefully acknowledged.

REFERENCES

Beeck A. (1992), "Strömungsfelduntersuchungen zum aerodynamischen Verhalten eines hochbelasteten Turbinengitters mit Kühlluftausblasung an der Vorderkante", Dissertation, Universität der Bundeswehr München

Domann A. (1988), "Aufbau und Erprobung einer schlierenoptischen Meßanlage am Hochgeschwindigkeits-Gitterwindkanal", Diplomarbeit, Institut für Strahlantriebe, Universität der Bundeswehr München

Merzkirch W. (1987), "Flow Visualization", Academic Press

Schardin H. (1934), "Das Toeplersche Schlierenverfahren", VDI-Forschungsheft 367, Ausg. B, Bd. 5

Schnerr G. (1988), "Digitale Bildauswertung für optische Strömungsmeßverfahren", DGLR-Bericht 88-04

Schreiber H.A., Starken H. (1991), "An Investigation of a Strong Shock-Wave Turbulent Boundary Layer Interaction in a Supersonic Compressor Cascade", ASME Paper 91-GT-92

Sturm W., Fottner L. (1985), "The High-Speed Cascade Wind Tunnel of the German Armed Forces University Munich", Paper presented at the 8th Symposium on Measuring Techniques for Transonic and Supersonic Flows in Cascades and Turbomachines, Genoa

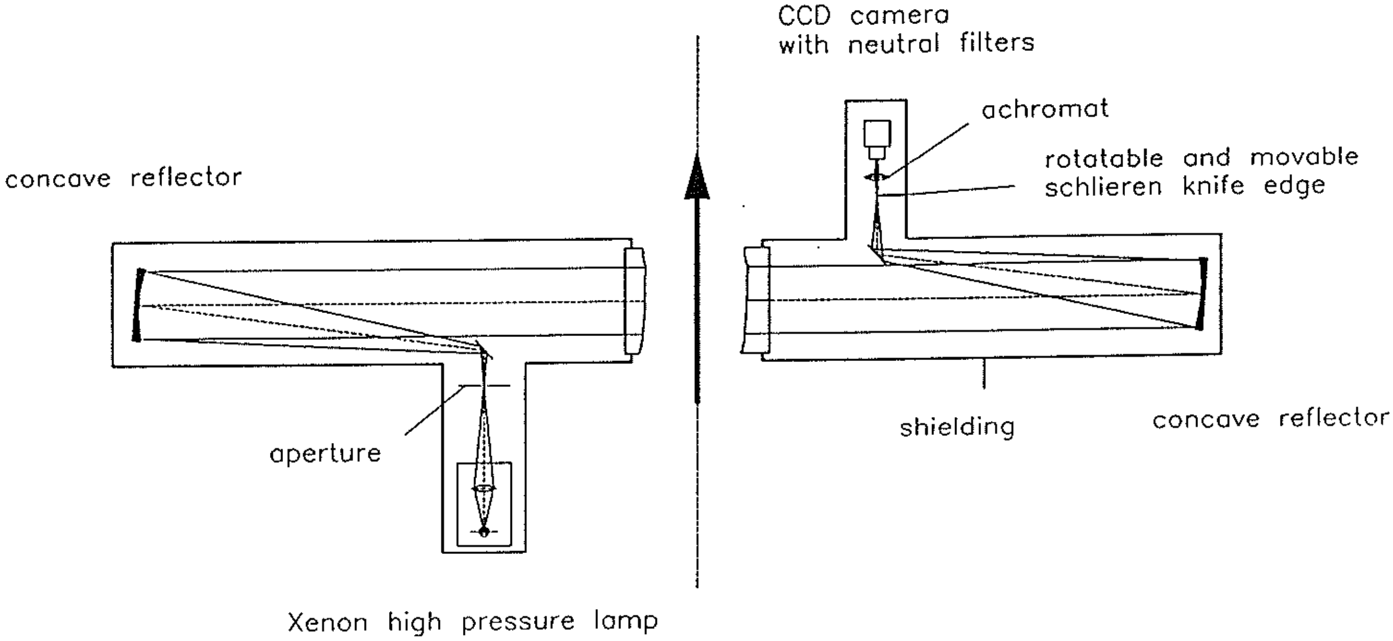


Fig. 1: Optical Setup of Schlieren Method

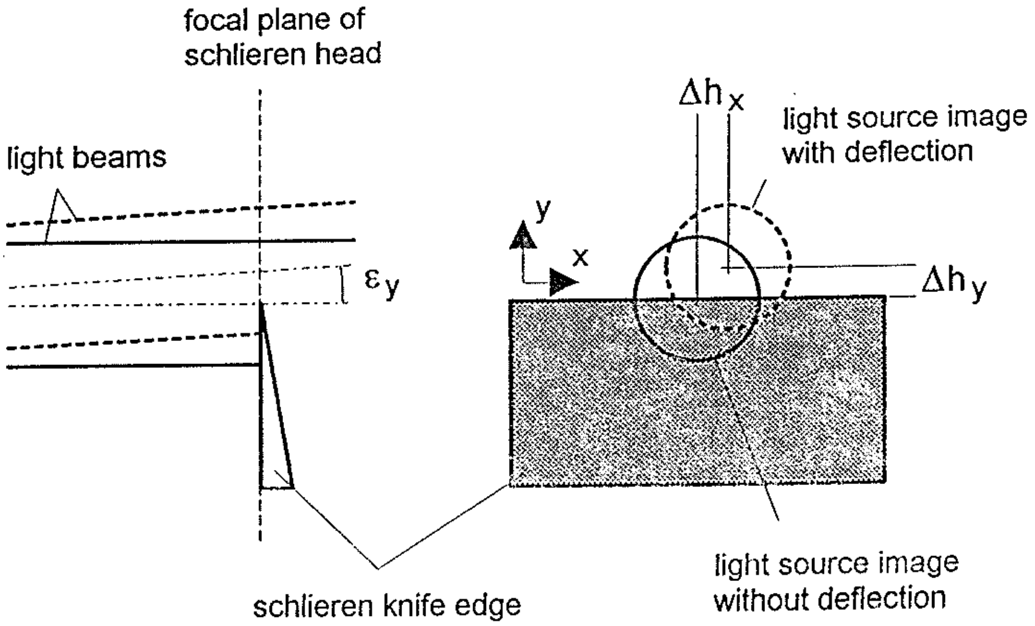


Fig. 2.: Visualization of Light Beam Deflections

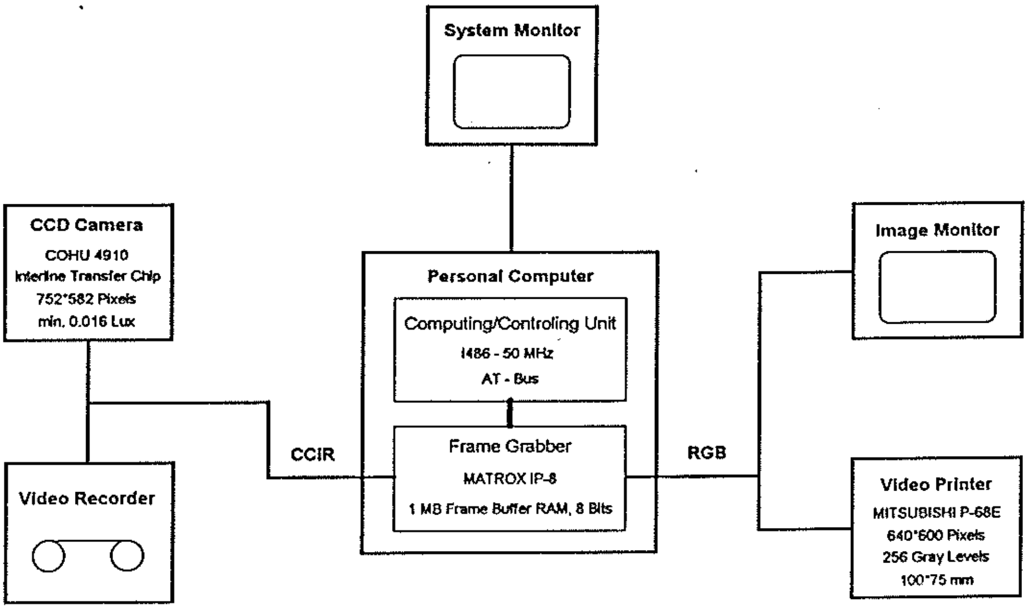


Fig. 3: System of Digital Image Processing

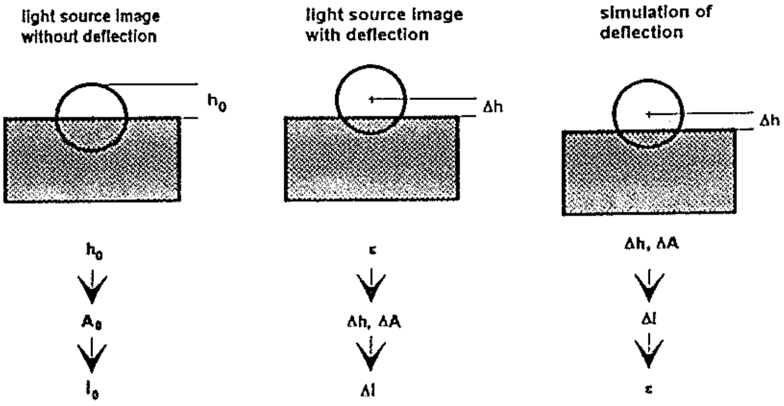


Fig. 4: Calibration Procedure

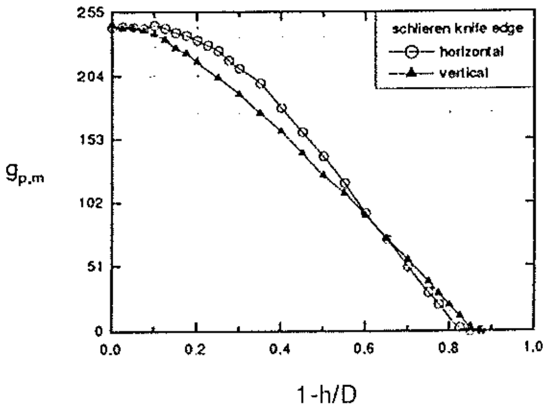


Fig. 5: Example of Calibration Curves

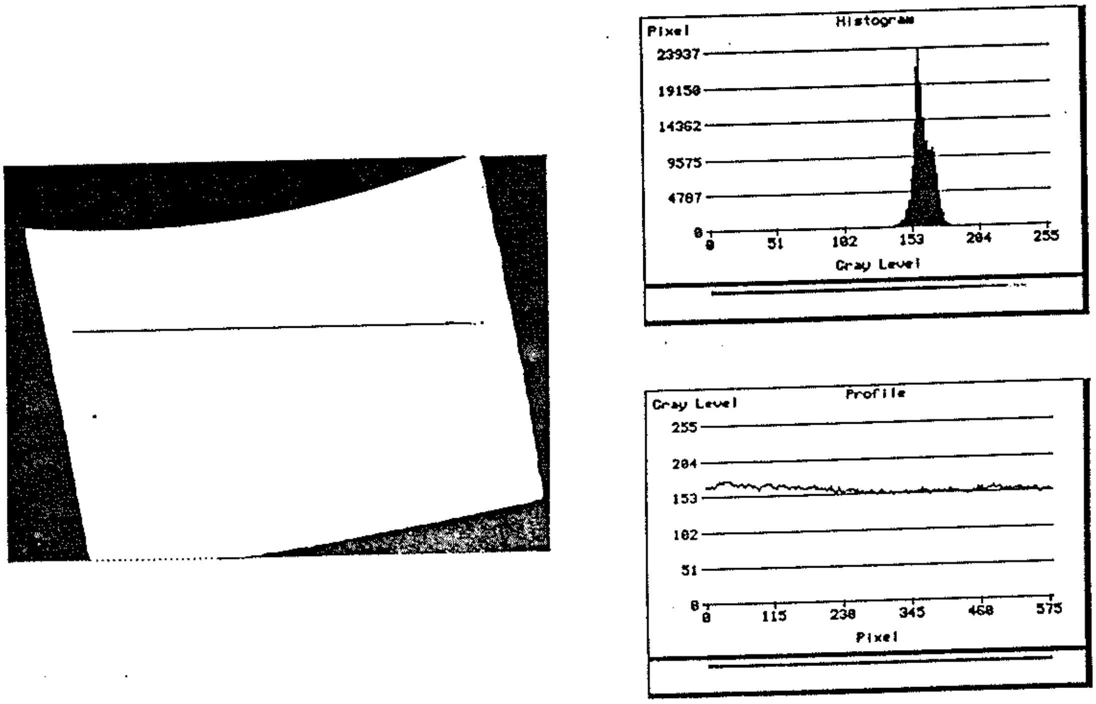
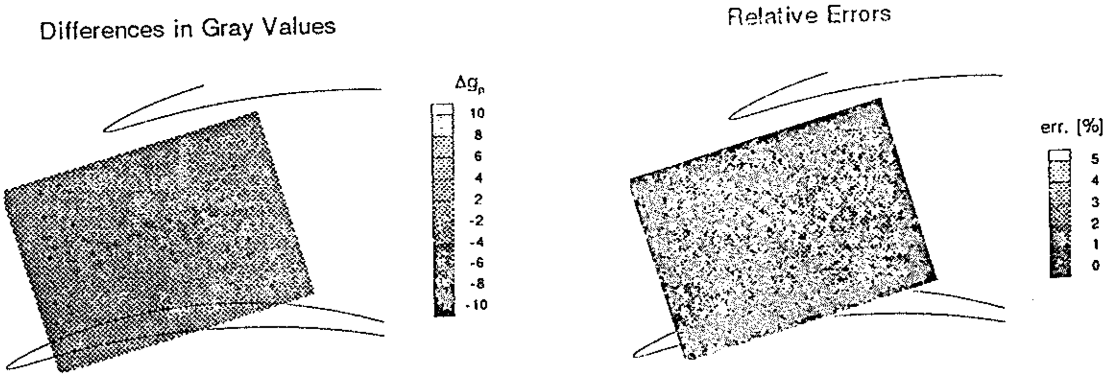


Fig. 6: Analysis of Schlieren Image without Deflections


Differences in Gray Values

Relative Errors

Fig. 7: Measurement Errors

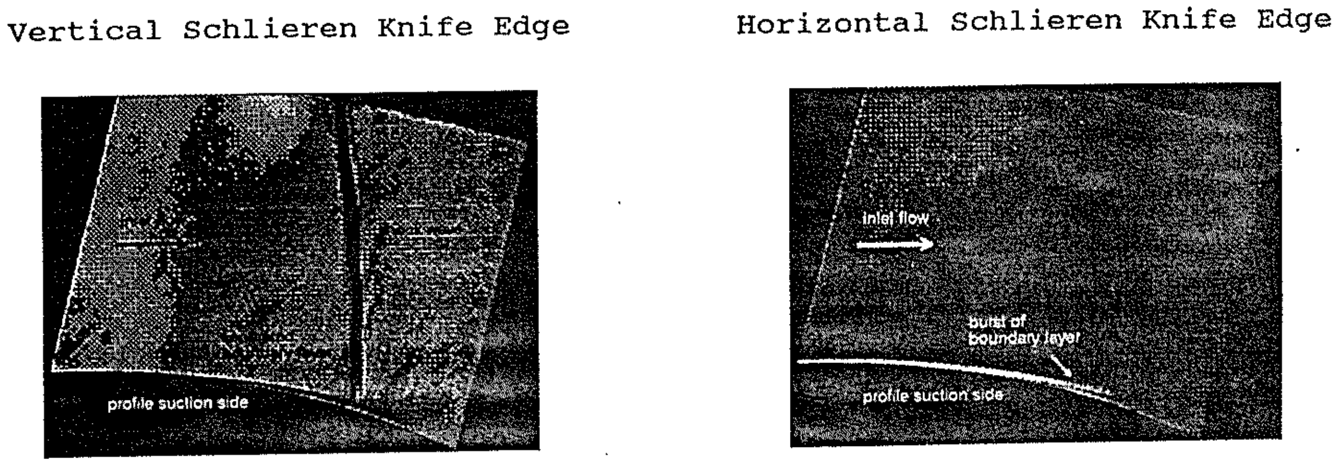
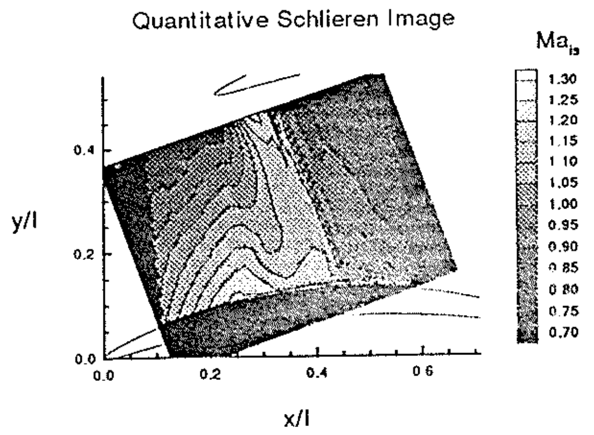


Fig. 8: Qualitative Schlieren Pictures of Transonic Cascade Flow



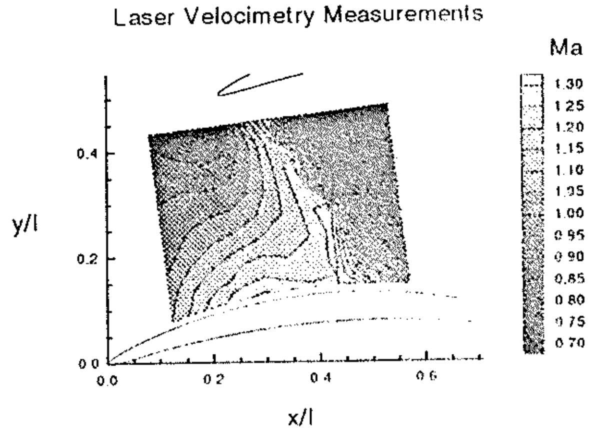
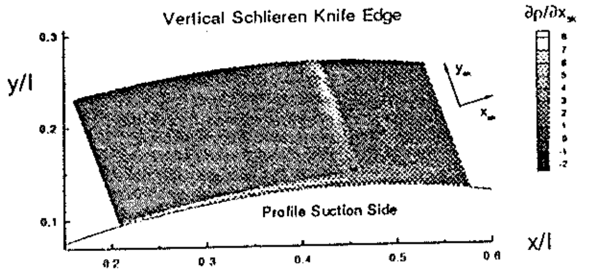
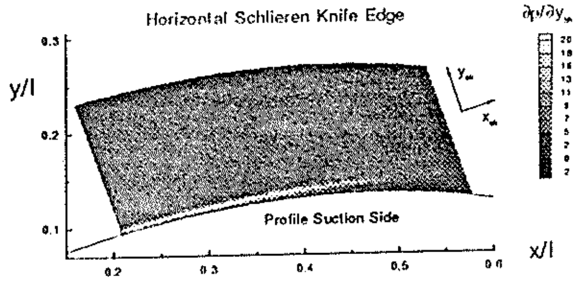


Fig. 9: Quantitative Schlieren Picture in Comparison with Laser Velocimetry Measurements





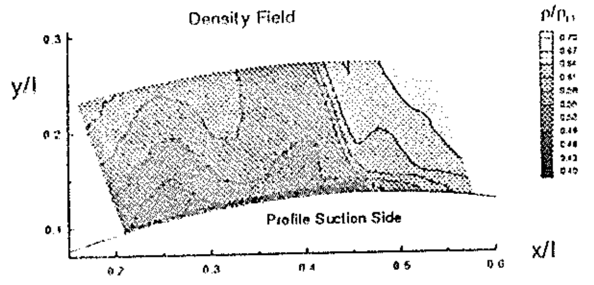


Fig. 10: Quantitative Results in the Region of Shock/Boundary-Layer Interaction