Background oriented schlieren (BOS) and particle image velocimetry (PIV) applied for transonic turbine blade investigations

S. Loose, H. Richard, T. Dewhirst, M. Raffel

Institut für Strömungsmechanik
Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Bunsenstraße 10, 37073 Göttingen, Germany

ABSTRACT

Turbine blade models equipped with film and trailing edge coolant ejection were investigated in the plane cascade wind tunnel of the DLR in Göttingen. The instantaneous velocity fields were quantitatively investigated by particle image velocimetry (PIV), and the density gradient fields were visualized by conventional schlieren photos, but also quantitatively determined by background oriented schlieren (BOS). The PIV measurements, but also the BOS measurements of the density gradient fields gave an insight into effects as for example the change of the compression shock strength depending on the coolant flow rate. The BOS technique can be seen as an simplified version of the well known speckle density photography and offers special advantages concerning the applicability. The experimental procedure and the results will be presented focusing on the metrological aspects. A numerical simulation of the flow velocity field and a numerically derived density gradient distribution based on computed light deflections will serve for a qualitative comparison with the optically obtained test data.

![Density gradients in a transonic flow (Ma_{in} = 1.2) in a plane turbine cascade wind tunnel determined by the background oriented schlieren (BOS) method. The gradient components dp/dx and dp/dy are plotted as vectors, which are color coded with the gradient magnitude. (Flow coming from above) ](image)
1 INTRODUCTION

The flow at the thick trailing edges of a turbine blade produces high losses, especially in the transonic flow regime (Sieverding et al. (1980), Sieverding (1982), Kost & Holmes (1985), Denton & Xu (1985), and Mee (1992)). Coolant ejection along the blade surface and at the model trailing edge significantly affects the overall flow field and partly reduces the aerodynamic losses. It is understood, that the study of this phenomena is of particular interest in progress towards more efficient turbines and power plants.

The schlieren photo, figure 2, gives an insight into the typical transonic/supersonic flow field at the rear part of a gas turbine profile. The base region containing recirculating fluid ends in a recompression zone where two shocks are generated. One of these shocks hits the suction side of the neighboring blade and interferes with the suction side boundary layer. The boundary layers at the trailing edge coming from suction or from pressure side are therefore different.

![Fig. 2: Density gradients in a transonic flow (Ma_{2x} = 1.22) in a plane turbine cascade wind tunnel determined by the classical schlieren method using a Toepler-wedge. The vertical gradient components dp/dy is grey-level coded. (Flow coming from above)](image)

On the lower side of the model the flow accelerates continuously towards the trailing edge. On the upper side the Mach number distribution has positive and negative gradients. This side is the suction side of the turbine blade, whereas the lower side is the pressure side downstream of the smallest cross section. Both sides were equipped with holes in order to eject different test gases for aerodynamic investigations of film cooling. A slot in the trailing edge with a width of 1mm serves to eject air into the base region simulating coolant ejection in the base region. Most of the tunnel occupation time during the test has been spent for detailed pressure measurements with tappings and probes at many different cooling air mass flow rates and different Mach numbers. Theses pressure measurements were mainly performed in order to get a reliable data base for future designs. Additional optical tests were done for two reasons: First, in order to demonstrate there applicability at this conditions, and second, in order to obtain additional information of the structure of the trailing edge shock system at various coolant flow rates. The measurements described here were performed by means of particle image velocimetry (PIV) and the background oriented schlieren (BOS) technique. These two techniques were found to
be well suited, as the investigations had to be carried out for several Mach numbers and coolant flow rates of the cooling air within very short time intervals. The instantaneous recording of the flow velocity fields does not only save tunnel operating time and costs, but also enables to study unsteady effects in the blow down facility. The tests have been performed in the EGG of DLR in Göttingen, which is a plane cascade wind tunnel allowing models with a chord length of 60 mm to be observed.

2 PIV MEASUREMENTS

![Velocity magnitude (pixel/s)](image)

**Fig. 3:** Instantaneous velocity field at the base region of a transonic blade (Ma\textsubscript{2is} = 1.22) determined by PIV. The velocity magnitude determined by the two-component measurement is grey-level coded. Dark areas mark outliers due to insufficient seeding of the cooling air or due to surface scattering at the model (Flow coming from above).

PIV measurements of the flow field have been taken at different cascade downstream Mach numbers (around Ma\textsubscript{2} = 1.2) at different coolant flow rates. The grey-level plot, shown in figure 3, represents the measured velocity magnitude. An arbitrarily chosen grey-level distribution has been chosen in order to enhance the velocity fluctuations for better representation. The instantaneous flow velocity field at the trailing edge with coolant ejection at Ma\textsubscript{2} = 1.2 and the terminating shocks at the trailing edge can easily be seen. The wake is significantly reduced by the cooling ejection. The data drop out in the wake – dark areas in the wake – are due to a reduced seeding density in the test gas that has been ejected from the trailing edge.

For this test, progressive scan, full-frame interline CCD have been used with 1024 by 1280 pixels resolution. Using a 32\(^2\) pixel interrogation window this translates to a spatial resolution of up to 32 by 40 discrete vectors. The seeding particles were DEHS droplets which are generated by means of Laskin nozzles. The aerodynamic diameter of the
particles was about 1 µm. The wind tunnel flow has been seeded in the settling chamber, the cooling air has been seeded downstream of the compressors. Due to the high pressure levels at this point the seeding density of the ejected air flow was slightly to low. The light source used was pulsed Nd:YAG laser with two independent oscillators. It was driven at a repetition rates of 10 Hz, the pulse energy at $\lambda = 532$ nm was 2 x 150 mJ.

3 BOS MEASUREMENTS

The principle of the background oriented schlieren (BOS) technique, which we used for our experiments can best be compared with the density speckle photography as described by Debrus et al. (1972), Köpf (1972), and in an improved version by Wernekinck and Merzkirch (1987). A description of the density speckle photography and the novel BOS technique is given at the same conference (Richard et al. 2000). In the following a short overview of the underlying principal will be given:

**Fig. 4:** Optical path for density gradient measurements by the background oriented schlieren technique

In a first step a reference image is generated by a recording of a speckle pattern through air at rest before the experiment. An additional exposure during the wind tunnel run leads to a second image (see Fig 4). This second exposure lead to a slightly distorted pattern in the image plane containing a shift of the speckles in areas were the light rays were deflected by the density gradients. The resulting images of both exposures can then be evaluated by correlation methods. In other words, without further evaluation efforts, algorithms, which were developed and optimized e.g. for particle image velocimetry (or other forms of speckle photography) can be used to determine speckle displacements. It can easily be shown, that the deflection of a single beam contains information about the spatial gradient of the refractive index, and therefore of the density, integrated over the optical path.
The main difference of the novel technique proposed in this article is, that in contrast to the conventional schlieren techniques the BOS technique does not require any optical devices on the sending side. The only optical part needed is an objective lens mounted for instance on a video camera on the receiving side. The camera used is focused on a random dot pattern in the background, which generates an image quite similar to a particle image or speckle pattern. For this reason we refer to this approach as background oriented schlieren (BOS). This procedure results in significantly reduced efforts during the application of the technique. However, the optical paths over which the density effects are averaged are divergent with respect to each other. This can result in a clear disadvantage when large viewing angles have to be used, but is of little influence for the recording distances of more than 3 meters used for the tests described in this article. For a later extension towards “Background Oriented Optical Tomography” (BOOT), which is proposed by G.E.A. Meier (Meier 1999), the divergence of the optical paths should be no problem since convolution methods for divergent beams are already known and described in literature (see e.g. Herman 1980).
4 NUMERICALLY SIMULATED PIV AND BOS RESULTS

The CFD results shown in the following were obtained by a 2D Steady Navier-Stokes code. The computation parameter differ from the experimental with respect to the shape of the blade and the Mach-number. The isentropic Mach-number was $Ma_{2is} = 0.9$ in case of the numerical simulation. Furthermore, no cooling air ejection has been considered in the simulation. Therefore, no qualitative fluid mechanical comparison can be done. However, the main features of the experimentally obtained flow field can be found and conclusion of the value of the proposed testing technique can be drawn.

Fig. 6: Grey-level coded velocity distribution of a transonic flow ($Ma_{2is} = 0.9$) in a turbine cascade determined by a Navier-Stokes simulation (Flow coming from above).
5 DISCUSSION

As already mentioned above, the optical tests with PIV and BOS were conducted in very short time in order to demonstrate the feasibility and worthiness of those optical tools. The computation of the light deflection were performed based on existing numerically obtained data in order to have a qualitative comparison. A quantitative comparison could not be shown, because of different parameters used during experimental and numerical simulations. However, the density and the velocity measurements of flow fields behind the trailing edge and the subsequent evaluation and analysis of pressure and velocity data yield information on the features of such flow fields and therefore show the value of those tests. In spite of difficult recording conditions the velocity and density gradient data obtained is relatively easy to obtain and is suited for comparison with data obtained by numerical simulations. Software determining the density distribution from the density gradient data has been written and tested but not yet applied to the data shown here. More results obtained by BOS and further results of the analysis software can be found in Richard et al. 2000.
6 REFERENCES


