

**Intra-Blade Quantitative Transonic Flow
Measurements at the DRA Pyestock Isentropic Light
Piston Facility Using Particle Image Velocimetry**

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Abstract:

The quantitative whole field flow visualization technique of PIV has over the last three years been successfully demonstrated for transonic flow applications. A series of such measurements has been made at DRA Pyestock. Several of the development stages critical to a full engine application of the work have now been achieved at DRA Pyestock using the Isentropic Light Piston Facility (ILPF) operating with high inlet turbulence levels:

- A method of seeding the flow with 0.5 micron diameter styrene particles has provided an even (20mm by 20mm) coverage of the flow field.
- A method of projecting a 1mm thick high power Nd/YAG laser light sheet within the turbine stator cascade. This has enabled a complete instantaneous intra-blade velocity mapping of the flow field to be visualised.
- Finally, software has been developed to automatically analyse the data.

The measurements provide an instantaneous quantitative whole field visualization of an unsteady region of flow; which has been compared with a full viscous prediction. This work represents the first such measurements to be made in a transonic annular cascade.

1. Introduction

Flow in turbomachines is highly unsteady, this significantly affects boundary layer behaviour. Important sources of the flow unsteadiness are the wake interactions and potential flow interactions, in most cases both mechanisms are occurring simultaneously. The potential influence however, decays much faster than the wake. In addition to these periodic fluctuations, strong random fluctuations can be observed indicating high turbulence levels, especially in the wake.

For many years considerable effort has been made researching methods by which three dimensional flow data can be extracted optically. Throughout the last decade several techniques have been developed.

Laser Doppler anemometry (LDA), which uses a continuous wave laser to temporally scan a single spatial point through the flow field has to date been the most commercially exploited technique. At face value the application of LDA seems straightforward. However, as the study of fluid dynamics has evolved towards dealing with the reality of three dimensional turbulent unsteady flows, the inherent limitations of temporally averaged data have become more apparent.

Alternatively whole field flow visualisation methods such as holography have failed to deliver a true solution to this problem for two main reasons.

deliver a true solution to this problem for two main reasons. Although holography has been developed as a diagnostic tool for visualising the turbine and compressor flows in gas turbine engines, the complexity of the holographic system has made its application unsuitable for the experimental case in question. Also, in some cases the complexity of untangling an integrated refractive index field adds a further limitation to the general application of the technique.

The more recently evolved technique of Particle Image Velocimetry (PIV) simplifies the acquisition of whole field data to a photographic process. This has been made possible by using the progress made in computer processing, the increased resolution of photographic films now available and the improvements in laser performance. It has recently been found possible to make quantitative measurements in relatively hostile industrial environments.

An example of this initiative is the PIV measurements made at DRA Pyestock on their short duration transonic annular turbine cascade facility. Quantitative measurements have been made using PIV and these measurements have been compared with a full 3D viscous prediction within the passage and wake regions of the flow through a single row of nozzle guide vanes (NGVs).

2. Experimental Facility

Testing was carried out in the ILPF at DRA Pyestock. This is a short duration facility designed to allow high quality heat transfer and aerodynamic measurements to be taken for a full-size annular cascade of turbine vanes. The use of this technique for turbomachinery measurements was pioneered by Schiltz et al, (1973). The Pyestock facility is described by Brooks et al, (1985). A schematic view of the ILPF is shown in Figure 1.

A light free piston is forced along a tube by high pressure air which compresses and thereby heats the air ahead of it. When a predetermined level of pressure is reached, a fast acting valve opens allowing the heated air to flow through the working

section and into a large dump tank. This gives steady operating conditions for the duration of the run, which can be varied from 0.5 to 1.0 second depending on the rise in air temperature required. The test conditions can be matched to engine values of both Reynolds number and Mach number. Engine values of gas-to-wall temperature ratio are also matched. All tests were performed with a turbulence grid at 4.5 axial chords upstream of the NGVs, giving an inlet turbulence level of 6.5%, as measured with a hot-wire anemometer. A major extension of the facility, to enable heat transfer data to be taken from a complete turbine stage, has been designed, built and is being installed.

An optical probe designed as a turbulence rod, see Figure 2, was fitted upstream as part of the turbulence grid for the passage measurements. For wake measurements, the probe was inserted downstream of the NGVs at approximately 4.5 axial chords. Table 1 shows details of the NGV operating conditions.

The predictions presented were carried out using the Dawes 3D Navier-Stokes flow solver (Dawes, 1986), using a grid of 74 axial, 25 radial, 25 tangential points on a sheared H grid as shown by Figure 3 which has highlighted the regions of interest for the tests. All computations were performed at the design, M- and M+ Mach numbers and a constant Reynolds number of 2.2×10^6 .

3. PIV Experimental Techniques

There were several specific areas of concern associated with the test. The technique itself had been evaluated previously (Bryanston-Cross et al, 1991) but there were other test specific areas of concern due to the requirement of measurements in the wake region.

To achieve a true validation of the flow it was considered important that the particle seeding was evenly distributed throughout the flow and be less than 0.5 microns in diameter. If the particles had a larger diameter than this, they would be unlikely to be able to follow the high turning angles experienced by the flow within the annular turbine cascade. The necessity of using particles of the

correct size is a problem well documented during the development of laser anemometry systems. In particular A. Melling, 1986 describes the need to use sub-micron seeding when visualising transonic shocks. It has also been the object of a recent study at MIT (Bryanston-Cross et al, 1990) where 200nm particles have been used to visualise the flow in a PIV experiment.

3.1 Optical System LFS (Laser Firing System)

The optical system was based upon experience gained performing a similar test within a transonic wind tunnel (Towers et al, 1991).

3.2 Nd/YAG Pulse Laser

The Nd/Yag pulse laser produces 100 mJ of energy in one or two optical pulses of duration 10 ns. The pulse separation can be varied from 20 ns to 1 ms in steps of 20 ns. The laser has a Gaussian beam profile which allows it to be focussed to a light sheet of 0.3 mm in width. The output wavelength of the laser was 512 nm which gives it a characteristic green beam. The repetition rate of the laser is 20 Hz.

The laser was operated remotely under a specialised computer controlled Laser Firing System (LFS). The LFS has been designed to operate within high electrical noise backgrounds and controls the laser firing to an accuracy of 10 ns in steps of 250 ns. The LFS was also interfaced to operate synchronously with the shutter of a camera which carried a diffraction limited lens. The shutter speed used was set to 1/15th of a second. In the tests performed the double pulse separation was set to 0.5 and 1 ms.

3.3 Diffraction Limited Optics

The receiving optics used in this test were based upon evaluations of many equivalent imaging arrangements. It has been found that the majority of commercial lenses, though being of a high optical standard compromise optical resolution for a wide field of view. This has led at times to a false assumption as to the minimum particle size which can be resolved. Commercial lenses are limited by

geometric optical aberrations. They are in some cases orders of magnitude less sensitive than those designed to operate at the diffraction limit of light. The diffraction limit is determined by the wavelength of light and is best described by the Abbe theory in Born & Wolfe, (1959).

The diffraction limited lens used for this experiment was based upon a conventional astronomical telescope, with a correction applied to allow it to image a particle within the range 0.1m to 2.4m. In effect the point image of the star has been replaced by the point image of the particle at a much closer range! In this test the diffraction limited lens was set to view the laser light sheet orthogonally. The lens was 0.7m from the test object with a magnification of 1:1.

3.4 Beam Propagation Optics

The objective of the beam propagation optics is to create a thin, approximately 0.3mm wide, sheet of laser light in the region of interest. This was achieved using a combination of lenses, the beam was first expanded through a spherical negative lens from within the laser. This produced a diverging beam of approximately 20mm diameter at a distance of 0.5m from the laser head. The beam was then shaped into a sheet by passing through a combination of positive and negative cylindrical lenses; creating a laser sheet of 40mm wide and 0.3mm thick, at a distance of approximately 1m from the last lens face. The beam was then reflected off a mirror at the bottom of the probe and into the region of interest. Two configurations were explored as shown by Figure 4 and Figure 5, representing measurements in the passage and wake regions respectively.

3.5 PIV Optical Probe Design

The optical access for the Nd/Yag laser beam was restricted to a hollow 7 mm outer diameter turbulence bar just ahead of the blade row. Figure 4 shows the turbulence bar. The problem was how to project a 100mJ Nd/Yag laser beam, which has an instantaneous energy power density of 100MW, though an aperture of 5 mm; without producing a local ionisation of the air or destroying

the optical surfaces used in the system. To evaluate the problem each aspect of the test was treated as a separate component. Firstly the beam was focused and reflected off a dielectrically coated optic. Dielectric optics were used as they have a low absorption factor and thus less likely to be damaged by the intensity of the laser beam.

The turbine vanes were manufactured in PERSPEX (see Figure 6) and the outer wall machined down to be identical to the annulus profile; thus providing a viewing window for the experiment which at a thickness of around 10 mm operated as a thin cylindrical lens.

Conventionally the surface of perspex is slightly roughened due to asperities. The window for this experiment has been polished to a glass like finish, they had also been heat treated to remove stress from the material. The window was made from two joined sections of perspex, which carried both the radius of the annular cascade and an amount of cascade passage contouring on its wall profile. It was found both experimentally and theoretically that the window curvature did not add a significant error in this application.

3.6 Imaging System

In the first test series performed at DRA Pyestock, a conventional SLR (single lens reflex) camera was used to image the particles. However, in the second test series the camera has been replaced by a diffraction limited lens. This has meant a significant increase in the quality of the optical data measured.

The net effect has been a lowering of the background noise in the image and an increase in the resolution of the data, (Towers et al 1991). This is particularly significant in the wake region, where the scatter noise generated by the light sheet striking the blade surface is much higher. The imaging system magnification was close to unity. Thus a 35mm x 40mm area directly behind the wake can be resolved to a photographic accuracy of 10 microns.

3.7 Data Processing

To date a high resolution film has been used for the PIV image recording work. Kodak TMAX has a resolution of 100 lines/mm and can be used at a sensitivity of ASA (ISO) of 1280. The resolution of the film used was 100 line pairs/mm. The potential accuracy of the measurement obtained at the film processing stage was 5%. The initial transonic work has been performed using a conventional high speed film, which had been developed to a speed rating of ASA 50,000. However, during a series of tests performed by the Warwick group it was demonstrated that the film can be replaced directly with a video camera.

3.8 Preprocessing and Data Analysis (AutoPIV)

The pre-processing of the data before computer analysis consisted of the following steps. The negative was developed by pushing it four times; thereby creating essentially binary pictures. Positives were then produced of the region of interest, ie the area containing the light-sheet image. These prints were then scanned using a HP scanner at 300 dpi to produce TIF format images.

AutoPiv is the result of a long period of research directed towards the automatic extraction of particle image data from stored digital images. Initially a direct (spatial) digital processing method was adopted. This approach was taken after reviewing the work of Goss, (1989). The particle data at transonic speeds tends to be sparse which makes the processing of individual particles far more attractive, than the global processing usually applied to low speed flows. There are several significant advantages of working with a direct image as opposed to the more conventional Fourier domain approaches of Adrain, (1985):

- 1 The spatial domain allows the use of well developed image processing algorithms.

2 The particle image field can be very quickly reduced to a sparse array of data points. Thus, instead of the intensive processing of large digital images, typically of the size of 8 to 20 Mbytes; the data is reduced to a single of 30 to 100 kbytes vector representing the particle field.

3 In making such a large data reduction it is then possible to apply simple but very intensive processing to evaluate the information.

The data presented in this paper was extracted by the development of a very simple and direct interrogation as follows.

Background Noise Elimination: Each particle is processed in turn. The first step in the algorithm is to discriminate between background noise and particle information. This is achieved by removing all the points which have only one pixel of data associated with them. The next stage is to sweep digitally a radius around the remaining particles. If an extra particle is found within this radius then it is assumed that the information has been erroneously generated by light scattered from the surroundings and not particle data. Particles found in this second category are termed as features and their overall outline can be viewed to assist the validation of the particle data.

Particle Pairing: AutoPiv has a detailed set criteria, allowing the user to enter the parameters of the experiment.

- i) Flow speed range;
- ii) Flow angle range;
- iii) Particle size range.

Within these parameters which are kept as wide as possible to minimise the risk of data conditioning, AutoPiv now inspects the particle vector file for potential pairs. Effectively two radii are drawn; an inner radius for the velocity minimum and an outer radius for the velocity maximum. The existence of a particle pair within this radius yields a velocity vector. The presence of a third or more particles

way, an instantaneous velocity map can be reconstructed from the vector information as far as the number of valid velocity vectors permits. The accuracy of the measurements is put at 4% of absolute velocity and is limited by the quality of the image on the film plane.

4. Experimental and Computational Results

Three conditions were analysed and compared to solver predictions; at design Mach number, below design and above design Mach number. Figure 7 shows a comparison of measured instantaneous velocities with predicted values for the transonic design condition (above design).

The measurements broadly agreed with the predicted values in all three conditions. The M+ condition was the condition to yield the best results in the sense that the measurements obtained were abundant enough to describe the flow over the whole area of interest. In the case of the M- condition, the results were also satisfactory but yielded fewer velocity measurements. The measurements under the design condition were in agreement with the prediction but were very sparse. This was due to a low concentration of seeding during the experiment. The ILPF is able to perform a test every half hour. However, the time needed to go through the whole photographic process is longer, so there is no possibility of analysing results within this timescale. Current work at DRA Pyestock is aimed at overcoming this problem by developing a PIV visualization system which yields the experimental results within this half hour period.

The measurements and predictions agree to within 3% on flow angle and 8% velocity magnitude for the M+ condition. The higher than expected velocity estimation error is due to two factors. The measured and predicted spatial regions are difficult to match exactly. The other factor being optical glare from the test cassette which occasionally causes the software to generate erroneous velocity readings.

5. Conclusions

Several novel experimental concepts have been developed (Bryanston-Cross et al, 1991) specifically for the Pyestock PIV application. This has resulted in the evolution of the technique from a laboratory exercise to an industrial application.

Instantaneous aerodynamic measurements have been made on a fully annular transonic turbine nozzle guide vane, at three engine representative conditions.

The 3D Dawes Navier-Stokes flow solver has been used successfully to predict velocity for the three conditions.

The flow-field phenomena measurements, as visualized by the PIV technique agree with those predicted by the solver.

The measurements made in this paper represent an almost instantaneous whole-field picture of an unsteady transonic flow in the wake region at a realistic stand-off distance; which could not have been made using conventional measurement techniques.

Acknowledgements

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References

Brooks, A.J. et al. "The Isentropic Light Piston Cascade at RAE Pyestock" AGARD-CP-390, 1985.

Schultz, D.L; Jones, T.V. "Heat transfer measurements in short duration hypersonic facilities" AGARD-AG-165, 1973.

Dawes, W.N. "A numerical method for the analysis of three-dimensional viscous compressible flow in a turbine cascade: application to secondary flow development in a cascade with and without dihedral" ASME paper 86-GT-145, 1986.

Bryanston-Cross, P.J; Epstein, A.H. "The application of sub-micron particle visualization at transonic speeds", Progress in Aerospace Science, Oct, pp 1-31, 1990.

Goss, L.P. et al. "A novel technique for blade-to-blade velocity measurements in a turbine cascade" AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterrey CA July 10-12, 1989.

Adrain, R; Yao, C. "Pulse laser technique application to liquid and gaseous flows and the scattering power of seed materials", Applied Optics, Vol 24, No 1, Jan 1985

Borne & Wolfe. "Principles of Optics", Pergamon Press, 1959.

P.J. Bryanston-Cross; S.P. Harasgama; C.E. Towers; D.P. Towers; T.J. Judge and S.T. Hopwood. "The Application of Particle Image Velocimetry to large scale Transonic Wind Tunnels" pp 289-296, Vol 23, No 5, 1991, Laser & Optics Technology

Melling A. "Seeding Gas Flows for Laser Anemometry", AGARD Conference, "Advanced Instrumentation for Aero Engine Components", Philadelphia, 19-23 May, Paper No 15, AGARD CP 399, 1986

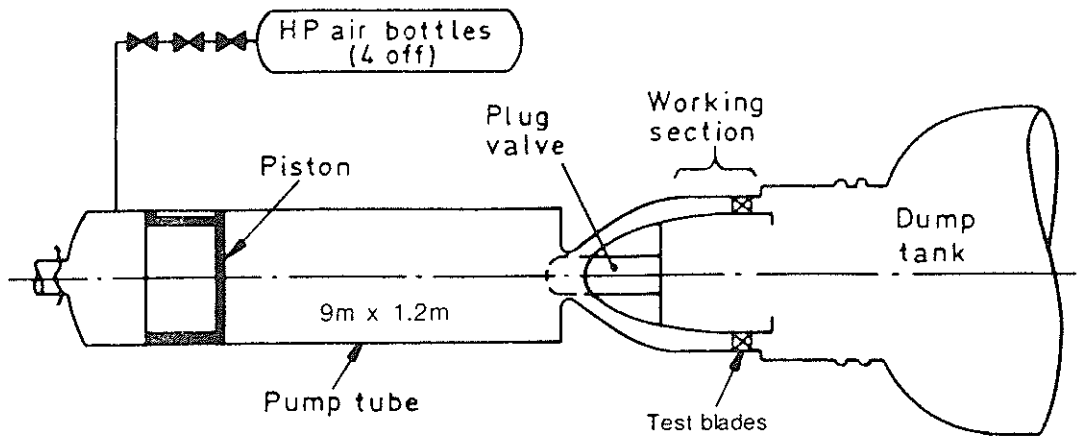


Figure 1. Layout of ILPF

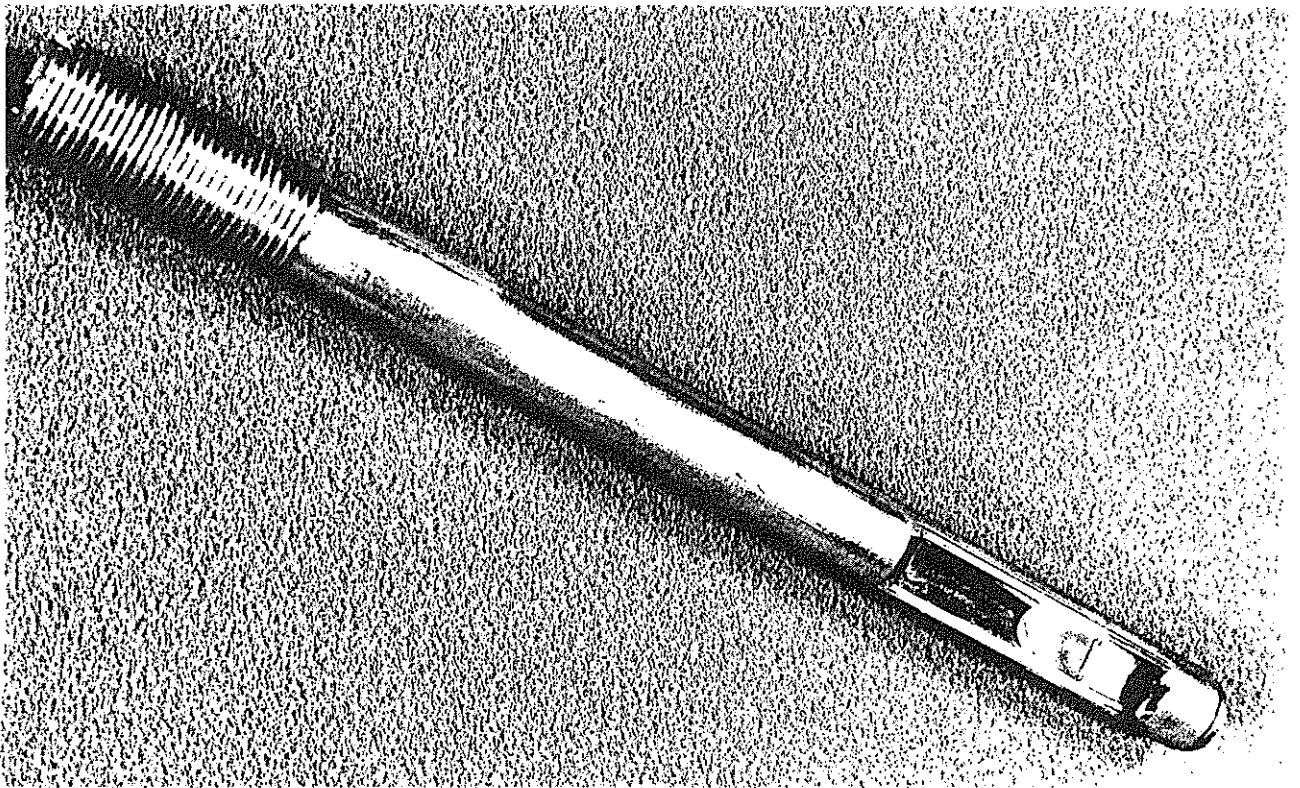


Figure 2. Optical probe

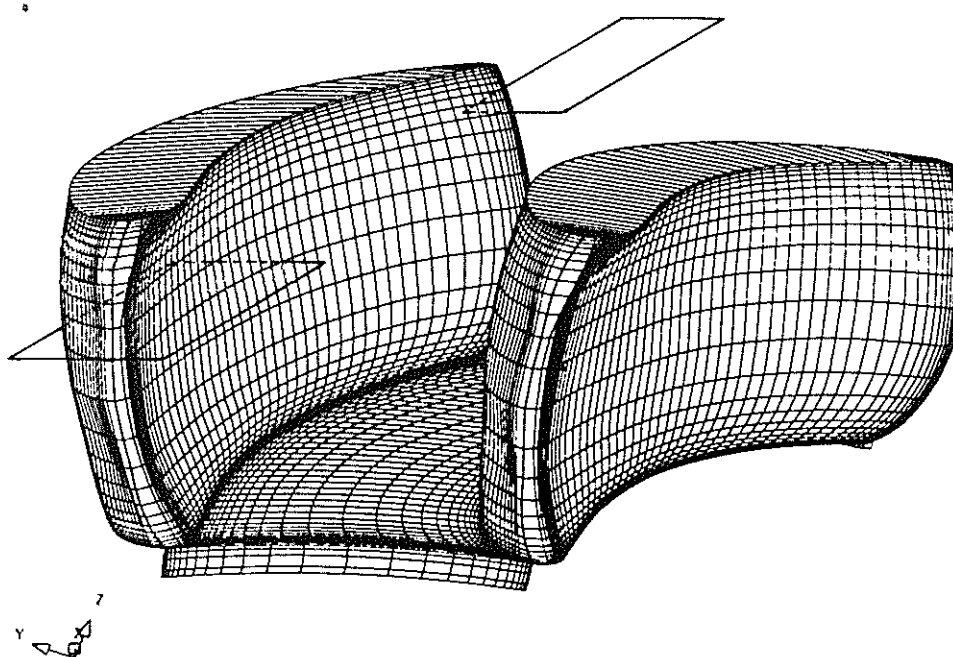


Figure 3. Computational grid

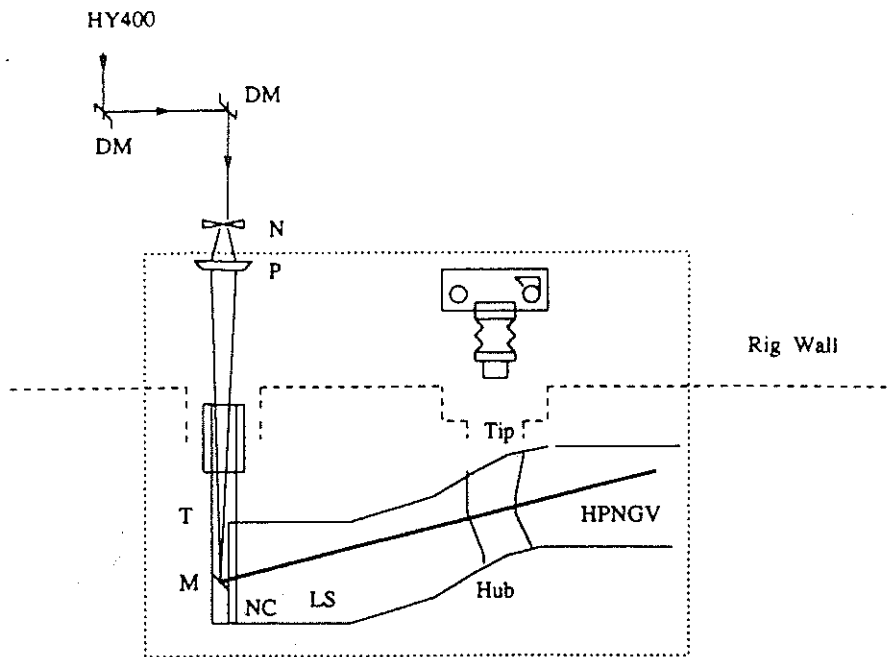


Figure 4. Optical setup for passage measurement

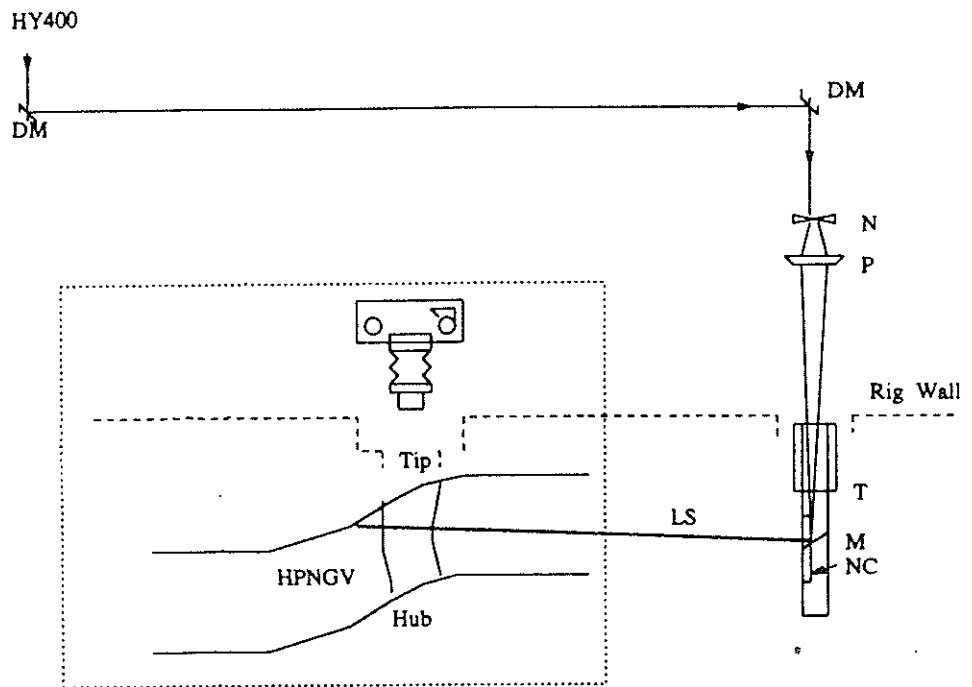


Figure 5. Optical setup for wake measurement

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|--|------------------------|
| Key: HPNGV - High Pressure Nozzle Guide Vane | DM - Dielectric Mirror |
| HY400 - Nd/Yag Laser | N - Negative Lens |
| P - Positive Cylindrical Lens | T - Turbulence Rod |
| NC - Negative Cylindrical Lens | M - Plane Mirror |
| LS - Projected Light Sheet | |

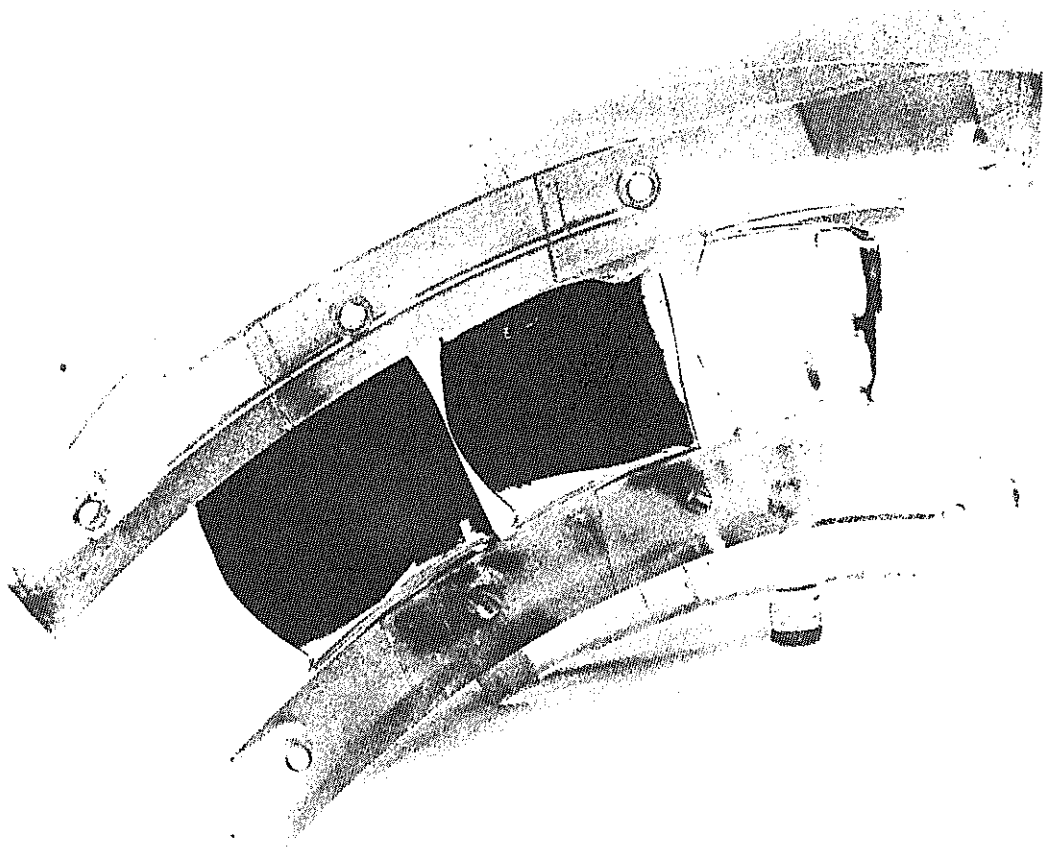


Figure 6. Perspex test cassette

Figure 7.
Measured and
Predicted
Instantaneous
Velocities

