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The Application of Particle Image Velocimetry (PIV) in
a Short Duration Transonic Annular Turbine Cascade

by

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R O Y A L A E R O S P A C E E S T A B L I S H M E N T

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THE APPLICATION OF PARTICLE IMAGE VELOCIMETRY (PIV) IN
A SHORT DURATION TRANSONIC ANNULAR TURBINE CASCADE

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SUMMARY

A series of experiments have been performed to demonstrate the application of Particle Image Velocimetry (PIV) to turbomachinery flows. The tests were performed at transonic speeds on a fully annular engine size turbine nozzle guide vane. The vane cascade was installed in a short duration Isentropic Light Piston Cascade (ILPC) test facility operating with high inlet turbulence levels.

The technique has been shown to map the whole flow field with a resolution of 0.5 mm. The quality of the results obtained are not significantly affected by local turbulence rates. The accuracy of the measurements is put at around 4% of absolute velocity and is limited by the quality of the image on the film plane.

The velocities derived from the PIV images have been compared with predictions from a three-dimensional viscous numerical calculation. It is shown that the experimental and predicted results are in good agreement. It is considered that this technique has considerable potential in application to turbomachinery flow field diagnostics.

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LIST OF CONTENTS

	<u>Page</u>
1 INTRODUCTION	3
2 EXPERIMENTAL FACILITY AND MEASUREMENT TECHNIQUE	4
2.1 The Isentropic Light Piston Cascade (ILPC)	4
2.2 PIV System	4
2.3 Hierarchical PIV System Evaluation	4
2.4 Laser System	5
2.5 Data Reduction System	5
2.6 Error analysis	6
3 RESULTS AND COMPARISON WITH COMPUTATIONS	6
4 FURTHER DEVELOPMENT OF THE OPTICAL SYSTEM	7
5 CONCLUSIONS	8
References	9
Illustrations	in text
Report documentation page	inside back cover

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The Application of Particle Image Velocimetry (PIV) in a Short Duration Transonic Annular Turbine Cascade

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ABSTRACT

A series of experiments have been performed to demonstrate the application of Particle Image Velocimetry (PIV) to turbomachinery flows. The tests were performed at transonic speeds on a fully annular engine size turbine nozzle guide vane. The vane cascade was installed in a short duration Isentropic Light Piston Cascade (ILPC) test facility operating with high inlet turbulence levels.

The technique has been shown to map the whole flow field with a resolution of 0.5 mm. The quality of the results obtained are not significantly affected by local turbulence rates. The accuracy of the measurements is put at around 4% of absolute velocity and is limited by the quality of the image on the film plane.

The velocities derived from the PIV images have been compared with predictions from a three-dimensional viscous numerical calculation. It is shown that the experimental and predicted results are in good agreement. It is considered that this technique has considerable potential in application to turbomachinery flow field diagnostics.

1. INTRODUCTION

Optical diagnostics have now become essential tools in turbomachinery for collecting, non-intrusively, velocity data of transonic airflows within the blade row. Laser anemometry in particular has become a routine test tool of which the two most established methods are L2F (laser two focus, Schodl, 1986) and laser doppler velocimetry, Strazisar (1986).

Both methods make single point measurements, whereas PIV is capable of collecting data in an entire plane of the flow field. In the case of L2F, significant periods of time can be required to construct a two-dimensional velocity map of the flow-field. This, for a continuously running test facility, can present the user with a prohibitive cost or, in the case of a transient running facility, severely restrict the data which can be collected. L2F is also difficult to use in a high turbulence environment.

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PIV as a technique was first described in the literature ten years ago by Meynart (1980). The original concept was to create a plane of light with a ruby pulse laser and photograph the motion of particles within it. The laser was used to form a double image of 10 micron particles within a low speed water flow. Having developed the particle images on a film they were then re-illuminated with a focussed continuous wave laser. If the re-illumination laser passed through a pair of particle images Young's interferometric fringes were formed. The spacing of the fringes is proportional to the velocity of the particle and the particle direction is orthogonal to the orientation of the fringes. An extensive review of the many parameters involved in the application of PIV have been made by Riethmuller (1988).

Historically it has been the analysis of the PIV data, stored on 35 mm film and containing of the order of 10 Mbytes of data, which has presented a computing bottleneck. However computational image processing algorithms considered impossible a few years ago are now commonplace. The processing of PIV images is now soluble using direct digital computational approaches. The method of data reduction applied in this paper is similar both to a method first reported by Goss (1989) and a direct video approach to PIV using a SIT (silicon intensified tube) camera developed by Wernet at NASA Lewis (1989).

To follow a transonic airflow a seeding particle must be of sub-wavelength diameter, as demonstrated by Melling (1986). A great deal of work exists relating to the light scattering properties of such particles. The Mie light scattering theory is described in detail in Born & Wolf (1959) and Van de Hulst (1957).

An excellent review of different seeding techniques for laser velocimetry has been published by Patrick (1981). Adrain (1985) states that there is a limiting balance between the amount of light scattered from a particle and the speed and resolution of the film required to image it. This is of particular importance when sub-micron particles are considered because the amount of light being collected is close to the minimum detection sensitivity of the camera and film combination, which has a direct effect on the application of the technique to turbomachinery. The calculations, though based

on fundamental optical wave theory, are empirically derived and do not take into account the effect of simple geometric lens aberrations as found in most conventional commercial lenses. As a result of this the potential sensitivity of the technique has been underestimated, this is demonstrated in Section 4 below.

PIV as applied by Bryanston-Cross & Epstein (1990) and now developed further at RAE has shown that it is possible to measure a whole two-dimensional field, instantaneous quantitative map of the velocity and flow direction within a transonic annular turbine cascade. Further experiments also show that PIV can be used with very low light levels which can result in its use with lower power lasers and at greater working distances than has hitherto been possible.

2. EXPERIMENTAL FACILITY AND MEASUREMENT TECHNIQUE

This section describes the short duration annular turbine test facility and the PIV system as used therein.

2.1 The Isentropic Light Piston Cascade (ILPC)

The Isentropic Light Piston Cascade (ILPC) is a short duration test facility capable of accommodating an engine size fully annular set of turbine nozzle guide vanes. The facility utilises a light piston to isentropically compress, and therefore heat, the test gas (air) prior to discharging it over the set of turbine vanes. The piston is driven along a honed steel tube by high pressure air (Fig 1) and once the desired operating pressure is reached a fast acting valve (plug valve) is opened allowing the air to flow over the blades. The facility simulates the correct aero-thermal environment of the real engine for 0.5-1.0 seconds. A detailed description of the facility is given by Brooks et al (1985)

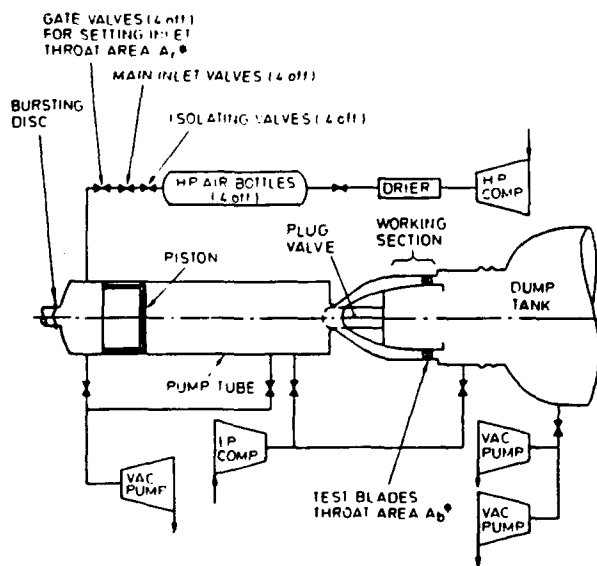


Figure 1 - ILPC Tunnel

For the present tests the facility was operated with a turbine vane cascade with an exit Mach number of 0.93 and Reynolds number of 3×10^6 . The facility was operated with a gas temperature of 335K for the PIV tests. The turbine vanes were manufactured in PERSPEX and the outer wall machined

down to be identical to the annulus profile. The final wall thickness was around 10 mm and operated as a thin cylindrical lens for the PIV tests. Fig 2 shows a photograph of the nozzle guide vanes mounted in a carrier cassette prior to inserting the test blades into the rest of the fully annular vane ring. The tests were performed with a turbulence grid upstream up the vane row which gave an inlet free-stream turbulence level of around 6% as measured with a Hot-Wire anemometer.

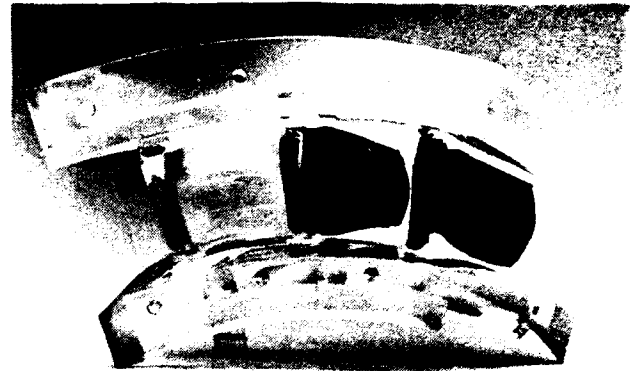


Figure 2 View of PERSPEX Nozzle Guide Vanes

2.2 PIV System

Much of the experimental method developed by Bryanston-Cross & Epstein (1990) has been found to be directly applicable to the tests performed on the ILPC turbine facility. A commercial particle generator was used to fill the pump tube with seeding particles prior to the run and a Neodymium-Yttrium (Nd/Yag) laser used to form the light sheet. The 500nm diameter styrene seeding particles used for seeding the flow were made from the description given by Hunter & Nichols (1985).

There were however several major differences:-

- i The ILPC consisted of a fully annular engine size nozzle guide vane cascade operating at transonic flow speeds and with a run time of around 1.0 second.
- ii The optical access for the Nd/Yag laser beam was restricted to a hollow 8mm outer diameter turbulence bar positioned 4.5 axial chords upstream of the blade row.
- iii The camera viewing window for the cascade was made from two joined sections of perspex. The window also carried both the radius of the annular cascade and an amount of cascade passage contouring on its wall profile.
- iv The whole operation was conducted from a remote station.

2.3 Hierarchical PIV System Evaluation

To ensure the successful operation of the PIV optical system it was evaluated in a hierarchical manner adding one level of complication at a time until the complete system was constructed. PIV is simpler to apply to transonic flows than many optical diagnostics because each element of the technique can be treated as an independent variable and tested as an isolated component.

i The Nd/Yag laser was first evaluated generating a 0.3 mm thick by 20 mm wide laser light sheet. A source of dielectrically coated mirrors was located and a series of tests were made at very high laser intensities to find if the coatings would damage. The results indicated that the coatings were adequate for the present tests.

ii The particle seeder was used to introduce 500 nm low speed styrene seeding particles into the light sheet and an 80 mm lens to image the particles within the light sheet.

iii The system was then set up with the test blade row on an optical table outside the rig facility. The seeder was directed through the blade row and PIV images were recorded using the 35 mm camera. The laser power output was normally 30 mJ/pulse and it was found that despite the effects of curvature and background scattered light a clear PIV image could be recorded.

iv The laser beam was then used to form the light sheet through a hollow 8 mm diameter turbulence bar. This was achieved by cutting a window in the bar and mounting a dielectric 5 mm mirror inside the bar to turn the beam. Again it was found possible to form the 0.3 mm width light sheet and record a PIV image through the cascade perspex window, as shown in Fig 3.

v The whole system was then reassembled in the annular cascade and a series of low speed runs were made. These being successful the transonic tests were started.

vi The seeding particles were introduced into the pump tube prior to the run and the piston utilised to "push" the seeded flow over the blade row.

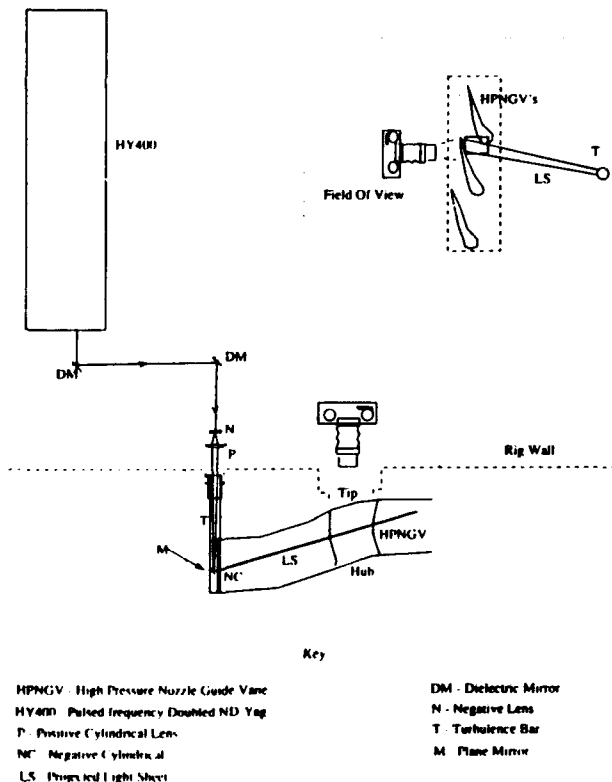


Figure 3 Nd YAG PIV Optical Light Sheet System

2.4 Laser System

The frequency doubled Nd/Yag laser produces two 10 ns 0.1 J pulses which can be separated over the range 50nsec to 100 microsecs at a wavelength of 532 nm. The Nd/Yag double pulse firing system had been previously only applied to holographic lasers. It was developed specifically for a PIV application jointly with a commercial laser manufacturer.

Several properties of the Nd/Yag laser helped in making the PIV imaging tests successful.

i The solid state Nd/Yag pulse has a well defined Gaussian beam profile, which was focused to produced a laser sheet of light 0.3 mm thick. A 'burn' pattern, obtained by placing a piece of laser analysis paper in the laser light sheet, was used to confirm the quality and width of the light plane.

ii The wavelength of the frequency doubled Nd/Yag laser was 532 nm. The Mie theory shows that the size of a sub-micron particle is related logarithmically to its ability to scattered light. Thus halving the particle size from 500 nm to 250 nm theoretically will produce a reduction by an order of magnitude in scattered light which can be collected in the side-scatter mode of detection. The frequency doubled Nd/Yag laser because of its shorter wavelength has a greater Mie scattering efficiency for sub-wavelength particles than the alternative Ruby pulse laser which operates at 695 nm.

iii A significant point made by Kompenhans et al (1986) is that a Nd/Yag laser can be run in an open lase mode at a repetition rate of 10 Hz; making the alignment of the optical system a simple task. With imaging focal plane depths which are of the same thickness as the light sheet, a significant error can be generated by an out of focus image.

iv All the high resolution/high speed photographic films investigated for this work have been found to have a wavelength cut-off in the 650 nm region, making them suitable only for application with lasers of shorter wavelengths.

2.5 Data Reduction System

The PIV image can be viewed directly on 35 mm photographic negatives; each image has approximately 200 to 500 particle pairs. Several systems have been evolved for the processing of PIV data. The first, evolved by Meynard (1980), used an optical Fourier transform to convert the particle data into essentially velocity and direction data. This is an elegant solution often used when the particle density in the flow is high, but not applicable to the sparse seeded case found experimentally in transonic flows. The method used to process the present data applies a digital image processing technique developed around a video capture system, as shown in Fig 4.

Essentially a standard photographic enlarger has been used to project a 5 to 10 times enlarged image directly onto a Charge Coupled Device (CCD) camera face. The spacing of the pixels in the camera is approximately 16 microns and the image on the 35 mm film is actual size. Thus the digital picture presented by the camera has a resolution of between 1 and 2 microns/pixel. The PIV image was moved across the CCD face with the use of two mirrors mounted on computer controlled galvanometers. This made it possible for a particle pair image to be viewed on one complete screen of a TV monitor. The position of the particles were then logged and stored in a computer. At an enlarger magnification of five the 35 mm film frame is equivalent to approximately 400 individual TV frames. To process one PIV whole field image requires the analysis of all these 400 frames. Currently the time needed to do this represents the slowest part of the technique.

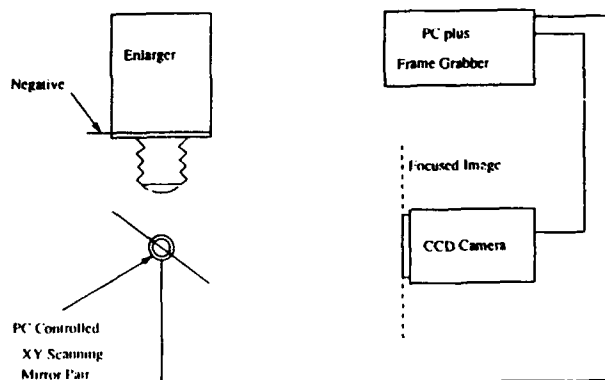


Figure 4 Data Reduction System

In the cases presented the film has been processed in a semi-manual manner, in that an operator has moved the film viewing one TV frame at a time. The operator moved the screen cursor to the first of a particle pair. The computer then computed the optical centre of the particle. The operator then moved the cursor onto the second particle in the pair. The computer was then used to find the centre of the points, log their position and compute the angle and speed of the particle. This type of system allowed initially a very simple image diagnostic tool. It was possible to view directly the images of the particles at a micron resolution level which made it possible to assess the signal to noise level of the films and to calculate the image size.

An example of a unprocessed PIV 35 mm photographic image is shown in Figure 5. In this image it is possible to identify the particle image pairs, the spacing between which changes with their speed. The data are then logged one TV frame at a time; the digital image shown in Fig 6 is an example of one such frame. The data can then be replotted as a vector field.

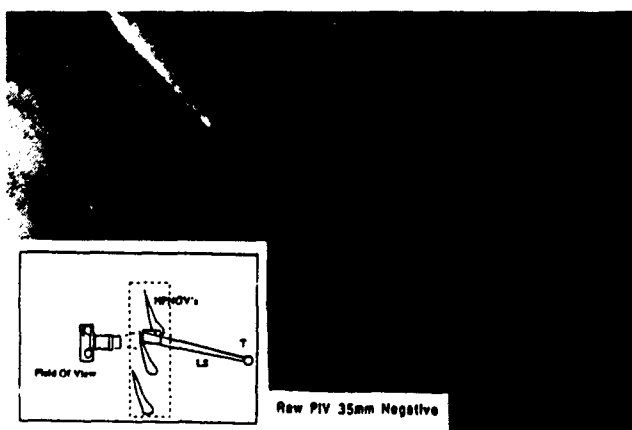


Figure 5 Raw PIV 35mm Negative

The best results came from images with between 200 to 300 particles in a 15 mm x 20 mm area. The size of the particle image was between 15 to 40 pixels in diameter. The ideal laser pulse separation was found to be that which produced an image distance between particles of 300 pixels. The exceptions to this were specific measurements made around the leading edge of the blade, where particle velocities were much slower and longer laser pulse separations were used. An imaging system of 1:1 was used on the camera and a magnification of ten in the enlargement/projection stage.

2.6 Error Analysis

The accuracy of the PIV system can be determined by direct measurement of an individual particle pair. Typically the image of the particle both for the RAE test and for the prior laboratory evaluation at MIT was found to be 60 microns in diameter and the spacing between a particle pairs of the order of 200 microns. The images shown in Fig 6 are typical of those used to generate the data shown in Fig 10. Photogrammetric distortion in the image has been determined directly by photographing a resolution test chart; this was found to generate less than 1% error in velocity estimate. Image processing software was written to locate the optical centre of intensity for each individual particle image. Given the nature of the images it is estimated that this can be achieved to an accuracy of 8 microns, which implies a photographic measurement accuracy of 4%. However if the particle is travelling through the light sheet at a significant angle or is in a flow region with high turning the calculated velocity will represent the resolved component as measured in the plane of light. This velocity estimate is comparable with the equivalent error in the distance between the two laser spots for a single shot L2F measurement.



Figure 6 Digitised PIV Negative Showing Particles

3. RESULTS AND COMPARISON WITH COMPUTATIONS

In order to assess the capability of the present PIV technique in making accurate gas path velocity measurements, the results are compared with predictions from a fully three-dimensional viscous flow solver. This flow solver, by Dawes (1986), has been rigorously evaluated and developed. It has been shown to be a reasonably accurate method of predicting turbine vane aerodynamics and secondary flows (Kingcombe et al, 1989 and Harasgama et al, 1990).

The grid used in the 3D Navier-Stokes solver is shown in Figure 7. The code was run with 25 (radial) $\times$ 73 (axial) $\times$ 25 (blade-to-blade) grid points. The inlet boundary layer profile was approximately 4.5% of span on both inner and outer annuli and consisted of a turbulent profile (velocity & total pressure). The solution was performed with the code operating in the fully turbulent mode and utilised the mixing length turbulence model.

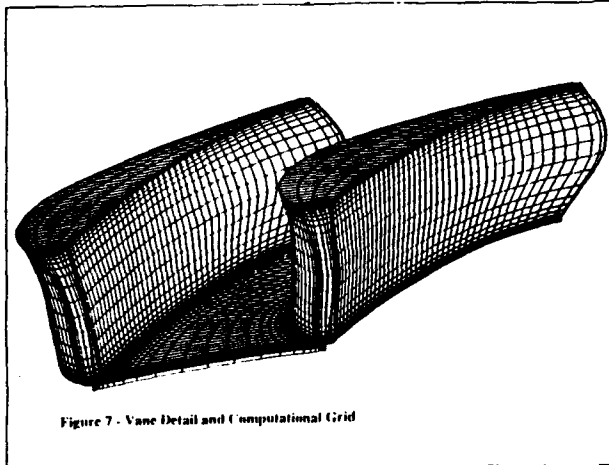


Figure 8 shows the predicted blade-to-blade flow field at the same radial plane for which the PIV data were obtained. This radial plane is a conic section which lies in the same plane as the light sheet used for the PIV measurements as shown in Figure 9.

The PIV measurements presented in Fig 10a are in good agreement with the theoretical plot shown in Fig 10b. The particles can be seen to accelerate and change angle as they pass through the blade passage. The particles are following the flow field, there is no evidence to suggest that the high turning present is centrifuging the particles towards the pressure surface of the blade. The information shown in Fig 10a represents an analysis of two 35 mm photographic negatives at the design Mach number condition. The first image was made at 500nsec pulse separation mapped the majority of the particles, whilst a second image made with a laser pulse separation of 1microsec was used to visualise the slower velocity particles near the leading edge of the blade row. The measurements and predictions for the present tests agree to within $\pm 3^\circ$ on flow angle and $\pm 10\%$ on velocity magnitude.

The restricted view shown in Fig 10a was as a consequence of the limited access to the experiment and the time available on the test. A lack of particle counts along the centre of the blade was the result of optical flare and distortion generated by the join-line formed by the two perspex halves of the cascade window.

4. FURTHER DEVELOPMENT OF THE OPTICAL SYSTEM

In the test performed at RAE a standard 35 mm SLR (Single Lens Reflex) camera and macro lens has been used to record the data. Macro lenses have been developed for photographic exercises where the image magnification is close to unity. They have a relatively wide angle of view and a compact form. The Macro lens was evaluated by the photographic department of RAE and was found to have a

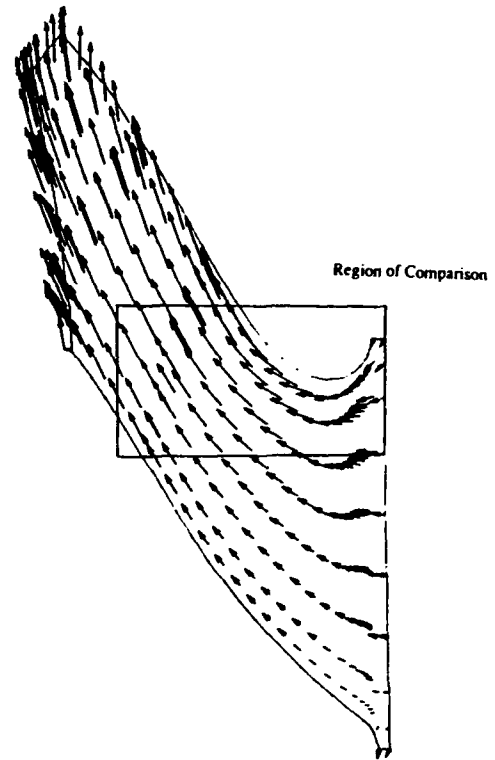
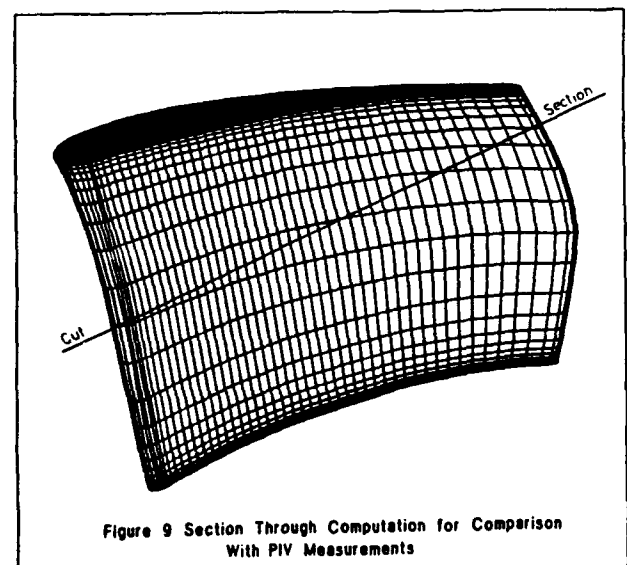


Figure 8 Numerical Vector Field



resolution of 30 microns, at a stand off distance of 0.125 m from the object. It was found to exhibit spherical aberration as its aperture was increased. It was also found difficult to collect particle data close to the blade surface because of flare from the solid surface.

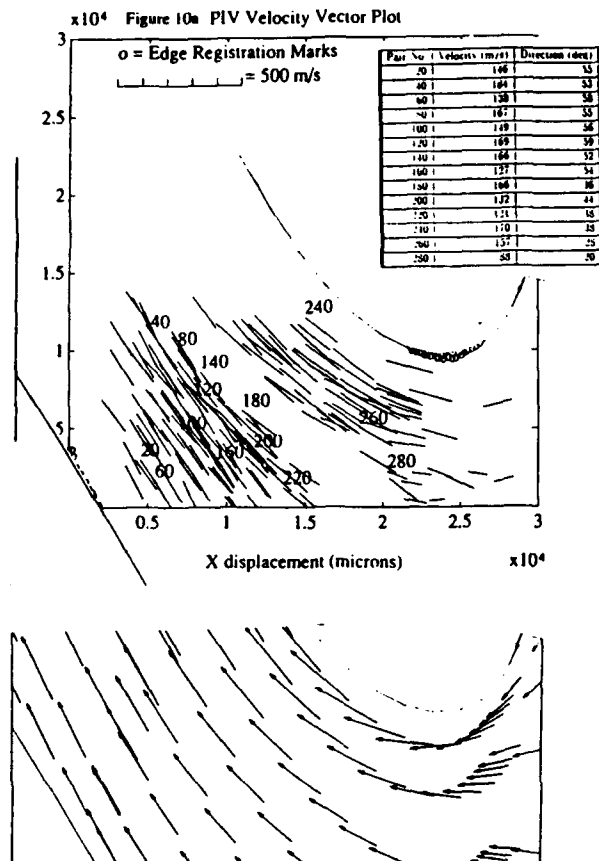


Figure 10b Computed Vector Field Scaled to Match Figure 10a

It had been considered that the type of lens used had little effect on the resolution of the information collected in PIV applications. The following test showed this not to be the case. It also demonstrated that there is a much wider application to turbomachinery than previously envisaged in the literature. The general application of PIV to larger flow installations, for example to make a measurement in a compressor fan or make a remote external aerodynamic measurement requires a lens with a small viewing angle and high spatial resolution. To investigate this a diffraction limited lens with a stand off range from 0.55 to 1.7 metres has been evaluated. A diffraction limited lens is one where the photographic resolution is limited not by geometric aberration but by the wavelength of light. The particular lens used was of a cassegrain design. This is similar to a miniature version of the design used for the Hubble Space Telescope, as described by Cavaghan (1990); for accuracy this uses mirrors instead of glass lenses. The lens was positioned 1.3 m from the light sheet. A plume of particles directly from the outlet of the seeder was observed in the plane of the light sheet. Images of the 500 nm seeding particles were recorded on high speed, high resolution photographic film and processed through the photographic enlarger as before.

A major advantage of a diffraction limited lens is found due to the small image size of the particle formed on the film, Fig 11. This allows a lower energy laser pulse to be used to obtain images for PIV. In practice an energy of 1 mJ/pulse at

a working distance of 1.3 m using the diffraction limited lens, compared to 30 mJ/pulse with a macro lens at a working distance of 0.125 m. Reducing the pulse energy also reduced the background flare from solid surfaces in the path of the Laser sheet, thereby improving the signal-to-noise ratio.

The authors see this a major step forward in the general application of PIV as a flow measuring tool and is a result not previously presented in the literature.

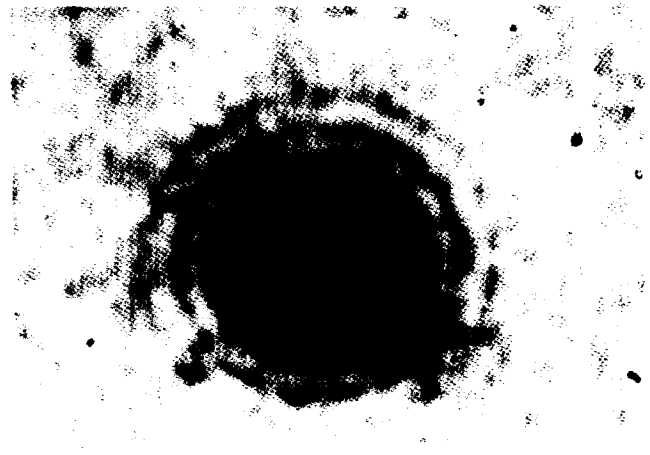


Figure 11 Diffraction Limited Image of 0.5 Micron Latex Particle, at 1.3m

5. CONCLUSIONS

This paper represents the first publication to show the application of PIV to a transonic flow within an annular turbine cascade using submicron particle seeding. It demonstrates a new direct approach to the extraction of quantitative whole field data.

The Nd/Yag laser developed specifically for this high speed application produced 100 mJ double pulses with a separation of 500 ns.

The particle seeding rate applied in this test was identical to that used in conventional anemometry and particles were sized in the flow field to be 500 nm in diameter.

The PIV measurements have been compared with predictions of the flow field using a fully 3D elliptical Navier-Stokes solver. These comparisons have shown good agreement.

The measurements made in this paper represent a nearly instantaneous picture of a large area of the flow, which could only be achieved by considerable traversing using conventional point measurement anemometers.

PIV can be seen as applicable to either a compressor or turbine, in either the rotor or stator cases. It would seem to be a quick method for mapping an unsteady flow field such as a three dimensional shock in a first stage compressor by making measurements at several radial planes.

It has been shown that the method can be developed to flow-field applications where a considerably larger standoff distance may be required.

The results presented show that the previous laboratory tests have now been applied in an industrial environment, using curved perspex windows without a loss in the quality of the data obtained. The test facility was not compromised in any respect to accommodate the optical system. The input Nd/Yag beam was 'piped' into the cascade to form a laser light sheet through an existing 8 mm turbulence bar.

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17. Abstract A series of experiments have been performed to demonstrate the application of Particle Image Velocimetry (PIV) to turbomachinery flows. The tests were performed at transonic speeds on a fully annular engine size turbine nozzle guide vane. The vane cascade was installed in a short duration Isentropic Light Piston Cascade (ILPC) test facility operating with high inlet turbulence levels. The velocities derived from the PIV images have been compared with predictions from a three-dimensional viscous numerical calculation. It is shown that the experimental and predicted results are in good agreement. It is considered that this technique has considerable potential in application to turbomachinery flow field diagnostics.					