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An Investigation of the Applicability of Tunnelling Velocimetry to Turbomachinery Research

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ABSTRACT: A new technique has recently been proposed to investigate the realities of unsteady flow, able to make three-dimensional, non-intrusive, instantaneous and simultaneous flow measurement of fluid velocity together with body near-surface pressure/temperature distributions using a single optical access point. The applicability of this technique to cases of interest in turbomachinery research is discussed and a specific application is described.

KEYWORDS: Turbomachinery, PIV, Tunnelling Velocimetry, PSP, TSP

1. INTRODUCTION

A variety of techniques have evolved to achieve fluid-variable measurement. Many are able to measure intrusively by point measurements, some are basically two-dimensional, while others are three-dimensional and non-intrusive but integrate in one of the three dimensions. In the last few years a lot of successful development effort has been oriented towards measuring velocity (Adrian, 1991).

Tunnelling Velocimetry (Funes-Gallanzi, 2000) is a development of the existing velocimetry whole-field methods, able to measure arbitrary velocity fields in a volume using a single optical access point. This technique brings together much of the recent knowledge gained in optical metrology, diffraction theory, luminescence barometry, thin films, and data analysis. Moreover, the method can potentially be extended to make fluid temperature, density and pressure measurements.

2. TUNNELLING VELOCIMETRY

2-1. Apparatus description

A prototype Tunnelling Velocimetry (TV) apparatus is shown schematically in Figure 1. A flow streams past a volume of interest. The flow is seeded with particles, such as polystyrene spheres. A collimated laser beam – typically vertically polarized – is introduced into the optical axis of a video detector by a polarizing beam-splitter arrangement illuminating the flow field. A quarter-wave retarding plate is placed between the polarizing beam-splitter arrangement and the volume of interest to circularize the polarization of the illuminating beam on its way to the measurement volume, and also serves to make the particle-scattered light horizontally-polarized on the return path. Thus, the polarizing beam-splitter arrangement transmits the scattered horizontally polarized light onto the imaging lens and CCD camera. Hence the name of the technique: it is as if the camera was viewing the particles, from whose motion velocity is derived, inside a lit tunnel. The laser is pulsed and the CCD camera records multiple images of the light scattered back by the seeding particles.

Light power density falling on the particles is lower than for Particle Image Velocimetry (PIV) for instance, since power is being distributed over a volume rather than a light sheet. However, the resulting light intensity scattered by the particles in this arrangement is actually higher than for a comparable light sheet (i.e. a light sheet of the same area at the focal plane) because the efficiency of back/forward scattering is much higher for micron-sized particles. A further advantage of this arrangement is that the drop in power density allows the use of conventional optical components, many of which have a power threshold of 0.1 Joules/cm. A ½-wave retarding plate is placed in the beam path before the beam-splitter, to be able to adjust the power to be transmitted to the measurement volume, and to provide power level measurement through a photodiode. The flow field images, captured after passing through a filter which excludes all frequencies other than that desired, are then processed through a computer system to extract the motion information. The velocity field can be derived in 3D from the time separation between pulses of light combined with particle displacements.

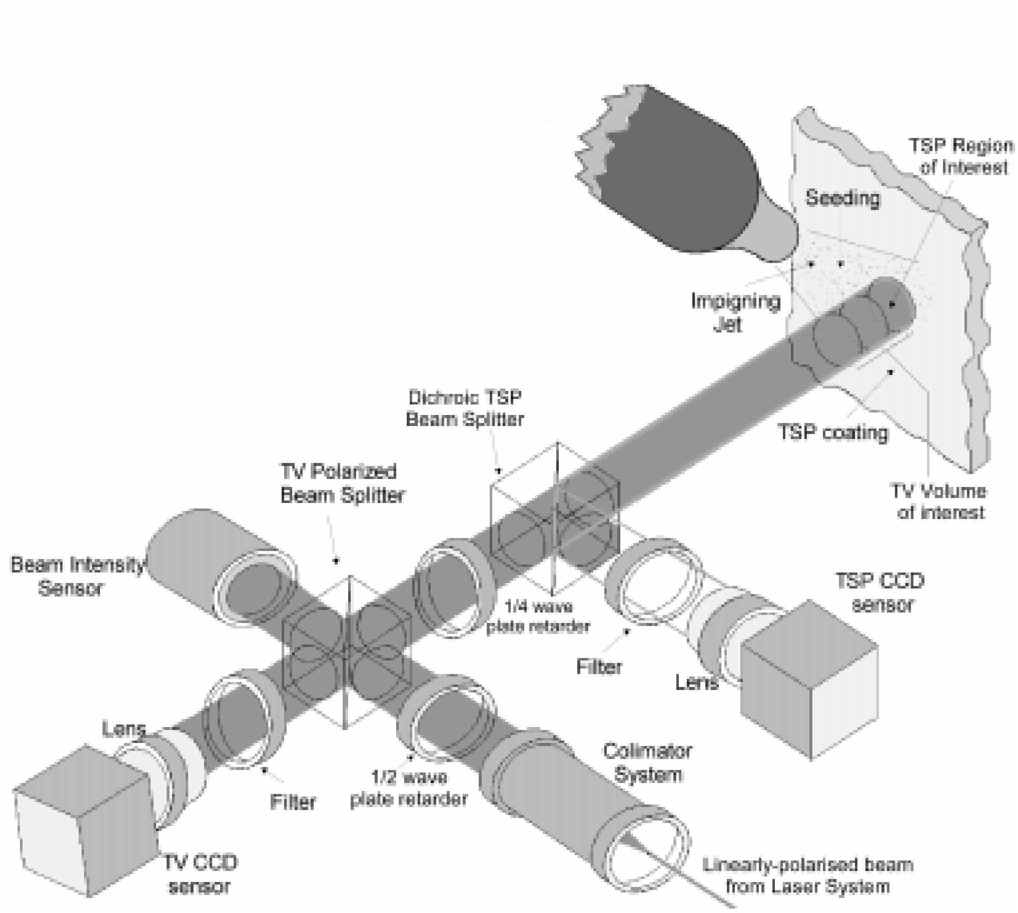

Figure 1 – Tunnelling Velocimetry (TV) schematic system diagram.

Furthermore, the color-sensitive beam-splitter in front of the ¼-wave plate is used to separate the fluorescent signal coming from near surfaces, redirecting it to the back-surface parameter-sensing camera. Pressure/Temperature sensitive paint offers a unique and inexpensive means of determining pressure and temperature distributions, impossible to obtain using conventional measurement techniques at a comparable measurement density (Mosharov et al., 1982). These paints can be excited either by the TV laser itself, or an external source such as an ultraviolet lamp.

The TV particle image field shows particle scattering images, which have to be interpreted to obtain particle position in three dimensions. This is quite a challenging step. An accurate analysis of the field preferably relies on generalized Lorenz-Mie theory (Gousbet & Gréhan, 1982) which is applicable to plane, Gaussian or elliptically shaped incident beams. As part of the project, a computer program has been developed capable of calculating the particle image, at the image plane of a simplified imaging system including aberrations, due to a plane, Gaussian or elliptical wave front in any beam position (Moreno et al., 2000). Using this method it has been shown that the intensity variation as a function of defocus, for instance, is not symmetric about the focus plane for micron-sized particles, and therefore there can be no ambiguity of particle position if particle images are used for positioning.

2-2. Initial Results

For practical applications, a low magnification is required in order to achieve adequate investigation regions. This objective can be achieved by considering in detail the effect of image digitization based on the concept of “locales” as applied to PIV (Havelock, 1989 & Funes-Gallanzi, 1998) and recently extended to 3D as a part of the same research programme. At low magnifications, the particle image is scrambled and the problem of inferring co-ordinates is more akin to cryptology. GLMT acts as the encryption algorithm, coordinate information is the key, and the low-magnification image is the enciphered message. Since GLMT is a smooth-varying function, it is possible to arrive at a solution by pattern matching, subject to digitization constraints. This topic is described in more detail elsewhere (Padilla Sosa & Funes-Gallanzi, 2000).

Figures 2 and 3 show a sample of the first sets of data obtained using this technique: a TSP plot of a hot (50 degrees) inclined jet impinging on a flat plate, and a double-pulse particle image field at a magnification of 1.7 illuminated by a 200 mJ per pulse Nd/YAG laser. The potential measurement density of Tunnelling Velocimetry can be calculated for a typical macro lens, starting from a comparison with PIV, to be close to that obtained for practical holographic PIV (Meng, 1994) of 0.5-1.0 measurements/mm^3.

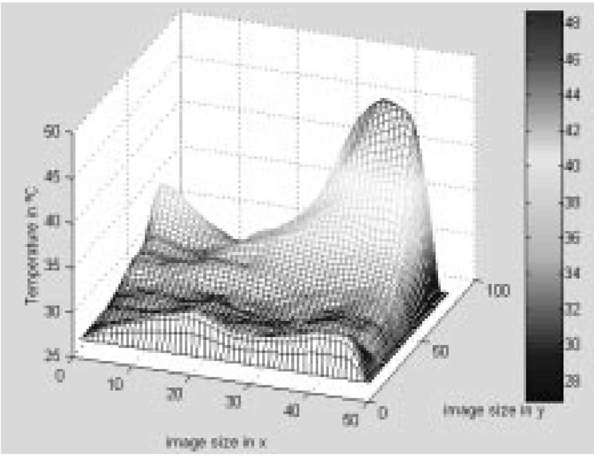

Figure 2 - TSP Measurement using TV apparatus

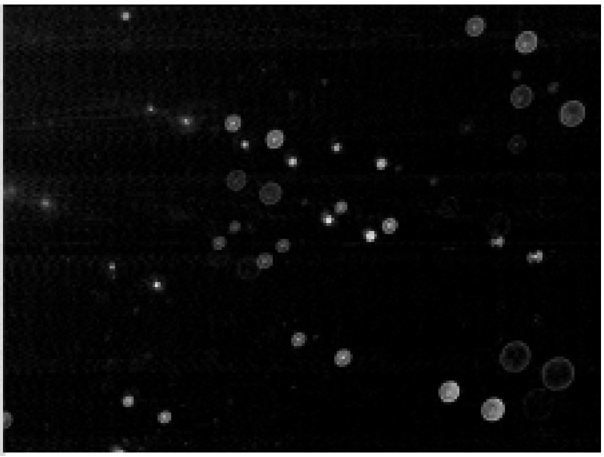

Figure 3 – Double-pulse TV data (M: 1.2, particles: 5 μm polystyrene)

3. APPLICABILITY TO TURBOMACHINES

3.1 Practical Considerations

The limited optical access normally afforded by turbomachinery and the complex geometries involved, make optical diagnostic measurements a challenging task. Glare from near surfaces is a source of particular difficulty, leading in some cases to the use of fluorescent seeding in order to overcome this problem. What experimental results there are using PIV of turbomachinery flows (e.g. Wernet, 2000) have been performed on single blade row or single stage rigs, and required optical access through a light-delivery probe from down/upstream. However, realistic turbomachinery flow conditions require a 1½ or 2-stage arrangement, so that up-stream flow and more particularly secondary flow characteristics coming into the testing blade row, are more representative of operational conditions. Figure 4 shows a two-stage air turbine rig representative of the intermediate pressure stage of power generation turbines. This rig is used to test new design concepts, where the testing row is the second stator blade row. In the case of power generation turbomachinery, the task of visualizing flow fields is made infinitely more difficult by the machine’s geometry, which yields no optical access from up/downstream.

However, both the aerospace and power generation industries are constantly seeking improvements in efficiency, performance and reliability, while meeting increasingly tight regulations for engine noise and pollution parameters. For instance, a prediction of the heat transfer to blade and endwalls is particularly important for an accurate assessment of turbomachinery component life. On the endwalls, there are complex 3D secondary flows present that make predictions of heat transfer difficult. In order to increase thrust-to-weight ratios and achieve maximum cycle efficiencies with gas turbine engines it is necessary to raise the cycle temperatures to the maximum, within constraints of structural integrity. Thus, the need to understand in detail and predict accurately the heat transfer distributions for high-pressure turbines becomes an important factor. The presence of complex three-dimensional secondary flows within the turbine passage makes the turbine designer's task very difficult and requires accompanying detailed aerodynamic information. Moreover, in turbulent flow conditions, where free-stream turbulence is high, heat flux on the blades is largely controlled by both free stream eddies of large size and energy reaching deep into the blade's boundary layer (Holmberg & Pestian, 1996).

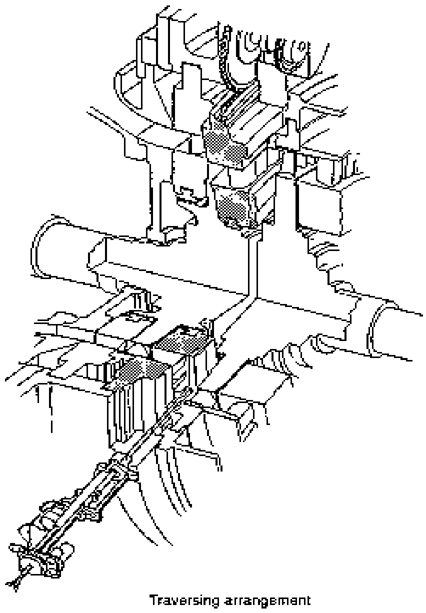

Figure 4 – Two-stage air turbine test rig.

Given that efficiency for turbines is already in the region of +90%, the areas where losses are generated and magnitude of these effects is small and difficult to investigate. The efficiency achieved to date is primarily due to the fact that turbine flow is dominated by the laws of conservation of mass, energy, and momentum. Thus, the remaining sources of loss are mainly related to viscous effects. Moreover, of the remaining loss, approximately half is due to secondary flow losses, with the remaining portion being due to components which cannot be decreased much and are only understood in a qualitative manner but cannot be accurately quantified, such as tip leakage loss and subsonic trailing edge loss. A further group of loss sources are not yet fully understood, such as endwall and transonic trailing edge loss, and these are further complicated by the unsteady nature of these flow fields.

Therefore, in an effort to satisfy the needs of industry, it was decided to develop Tunnelling Velocimetry, with the aim of making instantaneous non-intrusive 3D velocity measurements in the secondary flow region. This objective requires exploiting the capability of using a single optical access in a two-stage air turbine rig with an operating velocity downstream of the second stator blade row of approximately 0.5 Mach. As shown in Figure 4, the only optical path into the second testing stator/rotor flow region is through the conventional hot-wire traversing arrangement hole. This access is 15 mm in diameter wide by approximately 200 mm in length before reaching the flow passage. At the opposite side of the passage lies the blade root platform surface, which is of no immediate interest in terms of surface temperature or pressure. There are three options to deal with the beam reflected at this surface. Firstly, to coat it with a fluorescent paint emitting at a lower frequency, to trap the light at this surface, or lastly to polish it so it serves as a mirror, thereby enabling the viewing of the particles' scattering field in forward scatter, which is the most efficient. All of these alternatives are currently being investigated. Furthermore, in order to image the seeding particles, chosen such that they follow the flow field gradients faithfully, the required beam energy is of the order of 100 mJ per cm^2 per pulse of a frequency-doubled Nd/YAG laser, while the energy required by available PSP preparations is in the range of 10 mJ. Thus, there is a fundamental incompatibility between the light power requirements of the velocimetry component and those of the PSP. Much research currently centers on making changes to the PSP in order to be able to accommodate the higher power levels required by the velocimetry component. Early results are very promising and shall be reported elsewhere.

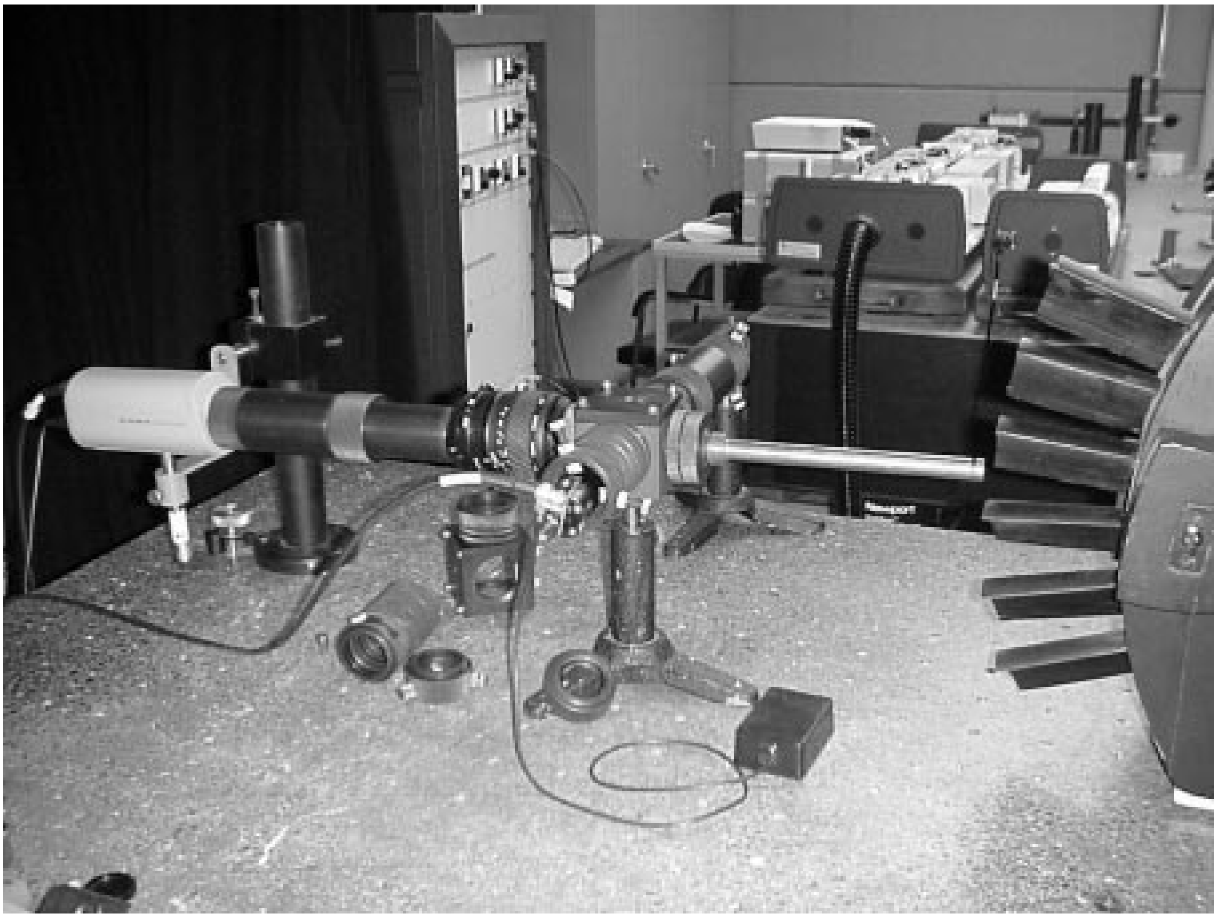

Figure 5 - TV prototype for turbomachinery research

Figure 5 shows the first design of the velocimeter for this application in the center of the image, fitted with a CCD camera on the left and on the right a maquette of the relevant part of the rig, including a stator blade row and rotor blades (not shown). A dual cavity frequency-doubled Nd/YAG laser used for thee tests can be seen in the background. The polarizing beam splitter arrangement at the heart of the velocimeter has subsequently been redesigned so it is able to cope with high beam energies, without suffering from low signal-to-noise due to secondary reflections. Furthermore, given the accuracies required by aerodynamicists at comparatively low magnifications, film (TMAX 3200) will be employed for the actual tests rather than the CCD shown in the figure.

4. CONCLUSIONS

Current research centers on testing this instrument on a two-stage air turbine rig. The aim of this experiment is to investigate secondary flow vortices. The measurement volume is to be reached by replacing a conventional traversing arrangement with a TV velocimeter and use a ND/YAG laser as the illumination source. We expect to be able to present early experimental results at the conference.

These concepts are at an early state of application and much work remains to be done but there is a myriad of application areas, ranging from turbomachinery, turbulence, automotive engineering to fluid mixing in chemical engineering. Tunnelling velocimetry is being successfully developed to enable the investigation of fluid velocity and interactions with surfaces through the boundary layer for instance. This technique opens the way for the investigation of previously inaccessible complex flow phenomena with high accuracy, using a robust and cost-effective means of measurement.

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