Tunnelling Velocimetry: consilience comes to the study of fluid dynamics

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Abstract

It has indeed been clear for some time that in the field of fluid dynamics there is a need to bring a "jumping together" of knowledge, by linking facts and theory across disciplines to create a common groundwork of explanation[1]. In order to describe the realities of unsteady flow, it is necessary to make three-dimensional, non-intrusive, instantaneous and simultaneous flow measurements of the four fluid variables: temperature, density, pressure, and velocity, sometimes together with body surface pressure/temperature distributions. A new technique has been developed which brings together much of the recent knowledge gained in optical metrology, diffraction theory, luminescence barometry, thin films, and data analysis. A single instrument has been developed, capable of making real-time 3D fluid velocity and near-surface temperature/pressure optical measurements non-intrusively, simultaneously and instantaneously, using a single optical access point. Moreover, the method can potentially be extended to make fluid temperature, density and pressure measurements. A prototype velocimeter is shown schematically in Figure 1. A flow streams along a profile. The flow is seeded with particles, such as polystyrene spheres. A collimated laser beam – typically vertically polarised - introduced into the optical axis of a video detector by a polarised beam-splitter illuminates the flow field. A quarter-wave retarding plate is placed between the polarising beam-splitter and the volume of interest to circularise the polarisation of the illuminating beam on its way to the measurement volume, and also serves to make the particle-scattered light horizontally-polarised on the return path. Thus, the polarising beam-splitter transmits the scattered mostly horizontally polarised 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. These concepts are at an early state of application and much work remains to be done but there is a myriad of application areas. Tunnelling velocimetry is being successfully developed to enable the four-variable investigation of fluids and their interactions with surfaces. This technique opens the way for the investigation of complex flow phenomena with high accuracy, using a robust and cost-effective means of measurement.

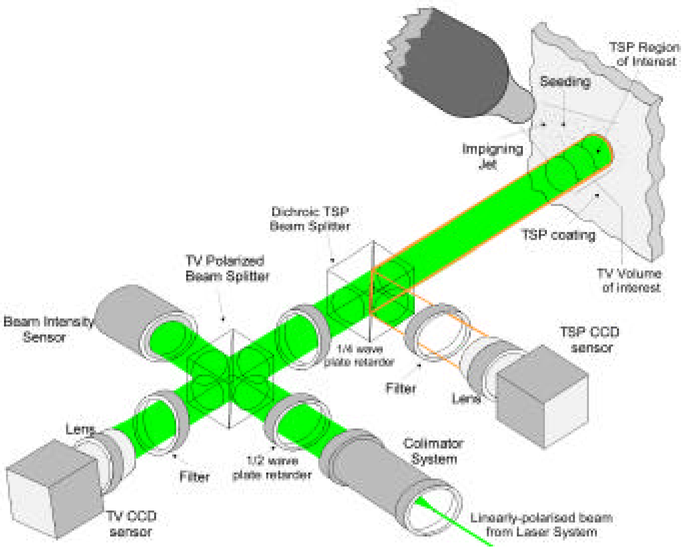

Figure 1 - Tunnelling Velocimetry (TV) system.

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Introduction

Aerodynamic structures commonly tested in a wind tunnel to gather data for use in verification of characteristics and in design improvements. Various quantities are measured in wind tunnel testing including the pressure distribution at the surface of the structure. The pressure information is used to calculate air flows and pressure distributions. Thus, aerodynamic structures can be economically "instrumented" for wind tunnel testing by painting them with a pressure/temperature sensitive paint (PSP/TSP), illuminating the structure with the required wavelength of radiation, and measuring the luminescence and light output intensities over the surface of the model using an optical imaging system. However, these measurements are often made over the entire structure and if corresponding aerodynamic information in a particular region is required, as it often is, it can be difficult to achieve registration.

Moreover, turbomachine predictions of heat transfer to blade and endwalls are particularly important for an accurate assessment of turbine component life. The presence of complex highly three-dimensional secondary flows within the turbine passage makes the turbine designer's task very difficult and requires accompanying detailed aerodynamic information. 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. Furthermore, flutter for instance is also an aero-elastic interaction between a body and fluid, which induces potentially catastrophic vibrations in both aircraft and turbines.

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 the fourth variable: velocity.

Existing methods of measuring flow velocity are mainly based on single-point Laser Doppler Velocimetry (LDV) and Laser-2-Focus (L2F) velocimeters. These techniques require scanning over the region of interest to obtain a whole-field velocity measurement and are therefore costly, time-consuming and primarily effective for steady flows, though there has been a shift towards developing the ability of LDV to deal with unsteady flows. For unsteady turbulent flows, several methods of whole-field measurement have been proposed, such as Doppler Global Velocimetry, Laser Induced Fluorescence, and Particle Image Velocimetry (PIV). This last technique has been very successful and shown to work in hostile industrial environments. Indeed, there has been a conducive scientific zeitgeist for the development of experimental set-ups where more than one technique is applied to measure more than one parameter, such as combining LIF and PIV.

PIV is a whole-field method of measuring fluid velocity almost instantaneously[2,3]. This approach combines the accuracy of single-point methods with the multi-point nature of flow visualisation techniques. Typically, a double exposure of the light scattered by particles introduced to the flow as seeding, when lit by a pulsed light source forming a thin light-sheet, is recorded by a camera during a short sampling period. The viewing position lies orthogonal to the light-sheet plane. The recording contains pairs of particle images, where their displacement encodes the velocity field. An analysis system is then employed which measures velocity from the motion information, given knowledge of the pulse separation between pulses.

PIV suffers from several major disadvantages. These include, among others, that the technique of dual-point optical access needed for orthogonal viewing a thin light sheet is intrinsically 2D, seeding side-scattering efficiency is very low, and it cannot cope with arbitrary velocity magnitudes. Alternative techniques for PIV three-dimensional investigation of fluid flow have been proposed, at the cost of increased complexity and optical access, and in some cases giving up a real-time measurement capability.

Another recent development in this area is Forward Scattering PIV, a microscopic technique, uses high-magnification forward-scattering information to yield 3D particle position information, though only within the instrument itself [4].

An even more recent development is that of Three-State Anemometry (3SA)[5], a derivative of PIV, which uses a combination of three monodisperse sizes of seeding to yield velocity, viscosity and density, by the differential paths of each seeding population. From the viscosity information, temperature can be derived, and by using the perfect-gas law (for the case of a simple Newtonian fluid like air) thermodynamic pressure too can be inferred. Here, for the first time, a technique exists that aims to make non-intrusive, instantaneous and simultaneous measurement of all four variables in a fluid flow. However, this technique also suffers from the same experimental deficiencies as PIV. Therefore, a 3D real-time velocimetry technique was required that only needs a single-access point, that can be combined with PSP/TSP technology, and with the potential to be extended to include full fluid variables measurement.

Tunnelling Velocimetry (UK and USA patents pending) originated from an Anglo-Mexican collaboration project, partly sponsored by the Royal Society, to develop a velocimetry capability in Mexico. Currently, work continues on various aspects of the technique, centred at the Mexican National Institute of Astrophysics, Optics & Electronics and Photon Imaging (USA). The technique for the first time offers the capability of combining 3D aerodynamic and surface heat transfer/pressure measurements.

Tunnelling Velocimetry

A prototype velocimeter is shown schematically in Figure 1. A flow streams along a profile. The flow is seeded with particles, such as polystyrene spheres. A collimated laser beam – typically vertically polarised - introduced into the optical axis of a video detector by a polarised beam-splitter illuminates the flow field. A quarter-wave retarding plate is placed between the polarising beam-splitter and the volume of interest to circularise the polarisation of the illuminating beam on its way to the measurement volume, and also serves to make the particle-scattered light horizontally-polarised on the return path. Thus, the polarising beam-splitter transmits the scattered mostly horizontally polarised 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 PIV, 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 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^2. 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 positions.

The viewing lens's characteristics and CCD sensor gain setting give the effective depth of field over which the camera will be able to record particle images. Thus the camera can view a "tunnel" of varying length.

The colour-sensitive beam-splitter in front of the ¼-wave retarder plate is used to separate the fluorescent signal coming from the object, redirecting it to the back-surface parameter-sensing camera[6]. 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[6]. 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 diffraction 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 Generalised Lorenz-Mie theory[7] (GLMT) which is applicable to plane, Gaussian or elliptically shaped incident beams, and has recently been extended to the case of spherical wave-fronts[13]. As part of the collaboration 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 illuminated 3D position[8, 14]. Figure 2 shows a radial intensity comparison between an experimental and a theoretical particle image, with an error of 9.9 grey levels RMS and a positional accuracy of approximately 5 μm at a magnification of 7.5. Such an achievement however, is insufficient to produce a practical system unless the magnification is low, in order to achieve correspondingly large investigation volumes.

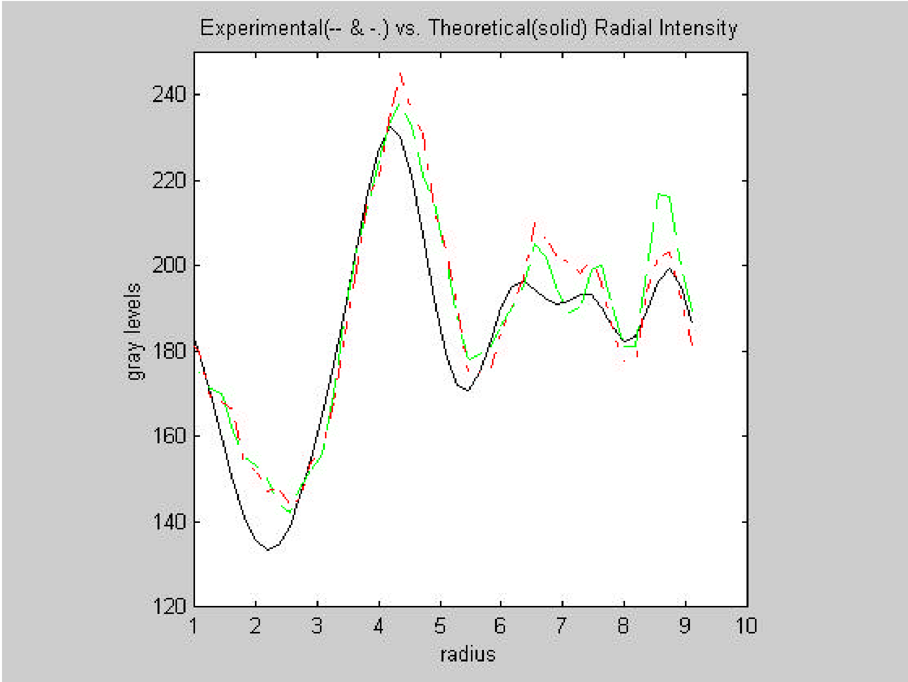

Figure 2 – Comparison between calculation and experimental particle image (glass, d_p=18µm & error (RMS)=9.9 grey levels).

Figure 3 shows the intensity variation as a function of defocus distance over a 1-cm depth of field for a forward scatter arrangement. Note that the intensity field is not symmetric about the focus plane and therefore there can be no ambiguity of particle position. The scattered intensity is displayed in Luxes as this measure makes it easier to adjust CCD cameras to the desired range of intensities.

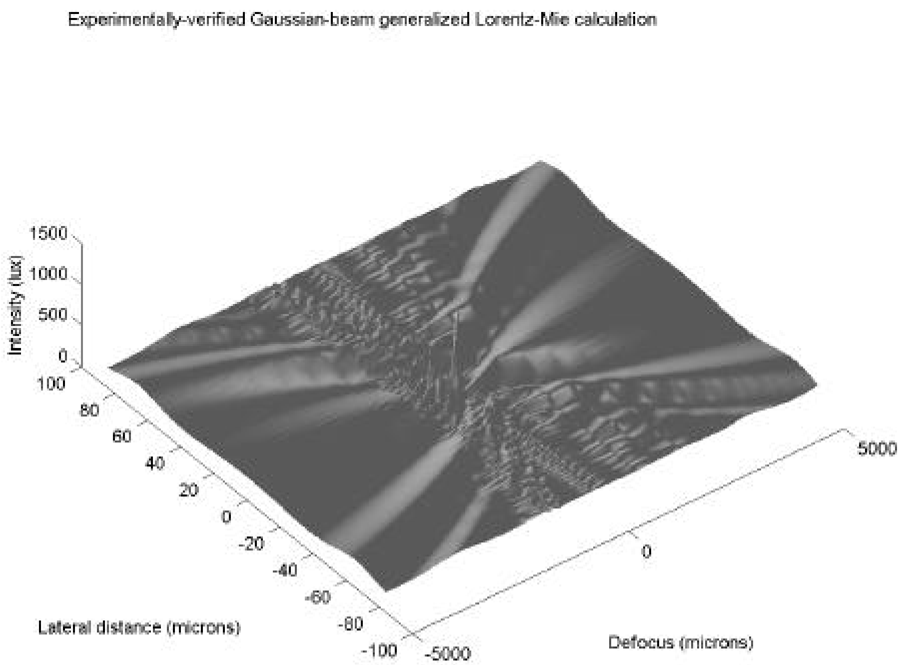

Figure 3 - Particle scattering intensity field as a function of defocus from -5.0 mm to +5.0 mm for a 21 µm glass particle.

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 digitisation based on the concept of "locales" as applied to PIV[9,10] 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, co-ordinate 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 digitisation constraints. Naturally, at low magnifications the positional accuracy is nevertheless diminished[15]. However, since TV analyses particle images belonging to a volume, rather than a light sheet as in conventional PIV, the probability of pair ambiguity is much reduced and so larger pulse separations can be used. This fact results in two advantages: increasing the distance travelled between pulses increases velocity accuracy, and the dynamic range of the method is also larger than for PIV. In initial tests, pulses separations about 5 times larger have been employed.

An important point to be investigated is how much detail can be glanced by sparse random 3D point measurements of a velocity field. In the 2D case where data refers to a light-sheet, two or three components of velocity can be readily related to a position. However, in three dimensions the minimum grid size must be derived based on the data field. To this end some work has been previously performed with the aim of producing a method which determines the optimum grid size for interpolated velocimetry data, without making any priori assumptions about the velocity fields, the system used or analysis method[16]. The method employs condition number as the main criterion for deciding the adequate grid size for a given data set and was developed for the case of PIV but it is equally valid for 3D Tunnelling Velocimetry. Data sets are directly comparable, independently of differing experimental parameters or data processing methods. This method illustrates the advantage of using velocimetry for unsteady flow research, i.e., using a comparatively small number of measurement points a detailed mesh of the underlying flow field can be derived. Thus, although velocimetry delivers a limited number of measurement points compared to Doppler Global velocimetry, for instance, which essentially yields a measurement per pixel, in general a high measurement data rate is not required to adequately reconstruct a flow field.

Conceptually, the grid separation determined by this method can be considered to yield an estimate of the number of mesh points required to compute an equivalent CFD field, which is much larger than the number of velocimetry measurement points. There are three sets of independent constraints in velocimetry measurements, which must be related. Firstly, the physical characteristics of the sensor with which the velocimetry image is to be recorded. Secondly, the range of scales in the velocity field under investigation (ranging from those of the same order as the characteristic length down to the Kolmogorov scale). Thirdly, once the data has been analysed and the velocity vectors calculated, the grid size for an interpolated representation of the continuos field must be defined. The unifying concept for these three constraints is the condition number. The latter can be regarded as the ratio of the resolution to the largest sensor axis in the first case, the ratio of the characteristic length to the Kolmogorov scale in the second, and the sensitivity of the approximating matrix to perturbations in the third. By setting the resolution to be equal to the Kolmogorov scale, the required sensor size and magnification are fixed and setting the resolution to be equal to the Kolmogorov scale makes the first and second constraints made consistent. The third constraint requires the determination of a grid size, which exhibits minimum error, without detailed knowledge of the velocity field under investigation. This is achieved by setting the condition number of the interpolation to twice the condition number of the flow field. Finally, the calculated grid size requires the number of mesh points, which need to be used to compare numerical calculations to experimental data. These concepts are at an early state of application to velocimetry analysis, and much work remains to be done. However, an analytical description of all the parameters involved are thus beginning to be developed to enable the implementation of high-accuracy measurements in all conditions. This approach opens the way for the investigation of complex flows with high accuracy and detail at the cost of extra processing, though this is increasingly economically feasible and widely available.

It is an important advantage for practical applications that the Tunnelling Velocimetry method uses virtually the same equipment as conventional PIV, except for the polarised beam-splitter and retarder plates. It is also a versatile technique because it includes variations such as off-axis and in-line holography, stereo viewing, image shifting for directional ambiguity removal, etc… some of which shall be discussed at the conferencein greater detail. Figures 4 and 5 show a sample of the first sets of data recently obtained using this technique, of a TSP plot of an hot (50 ^{o}C degrees) inclined jet impinging on a flat plate, and a particle image field at a magnification of 1.2 illuminated by a 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 holography[11] of 0.5-1.0 measurements/mm^3.

Figure 6 shows a side-view of the scattering field shown in Figure 3, which shows a particle illuminated by a Gauβian wavefront and viewed at a distance of 12 cm by a 90 mm SIGMA macro lens. Several points can be illustrated using this figure. The plot shows the on-axis intensity (Poisson Spot) with a solid line, the maximum intensity of the scattering field with a dotted line, and the minimum intensity is shown with a dashed line. Firstly, it is clear that it is important for ease of camera calibration to carry out this type of calculation in Luxes. Thus, knowing the minimum sensitivity of the camera and the largest intensity to be measured, the gain can be calculated with the gain set to "manual", as the automatic gain control makes the whole approach impractical. In this forward scatter arrangement it is comparatively easy to adjust the camera, as the mean background level to which the field tends, i.e. 250 Luxes, can be set equal to mid-range grey levels (for instance 128 grey levels in an 8-bit system) by sufficient defocusing. The peak intensity is then clipped at peak levels where position is estimated taking this clipping into consideration. Secondly, if the black-clip is set at a suitably large level such as 350 Luxes in this case, the particle will only be visible in a depth of field of less than 0.5mm and so the measurement will be essentially a 2D measurement, though the whole volume might be illuminated. Thirdly, it can be seen from the dashed line that information is contained not only by the peaks but also by the minima of the scattering field. Fourthly, the dotted line shows clearly how the maxima provides information about particle position over a range of almost 1 Inch, while if one considers simultaneously the maxima and minima we can see that information extends beyond 30 mm.

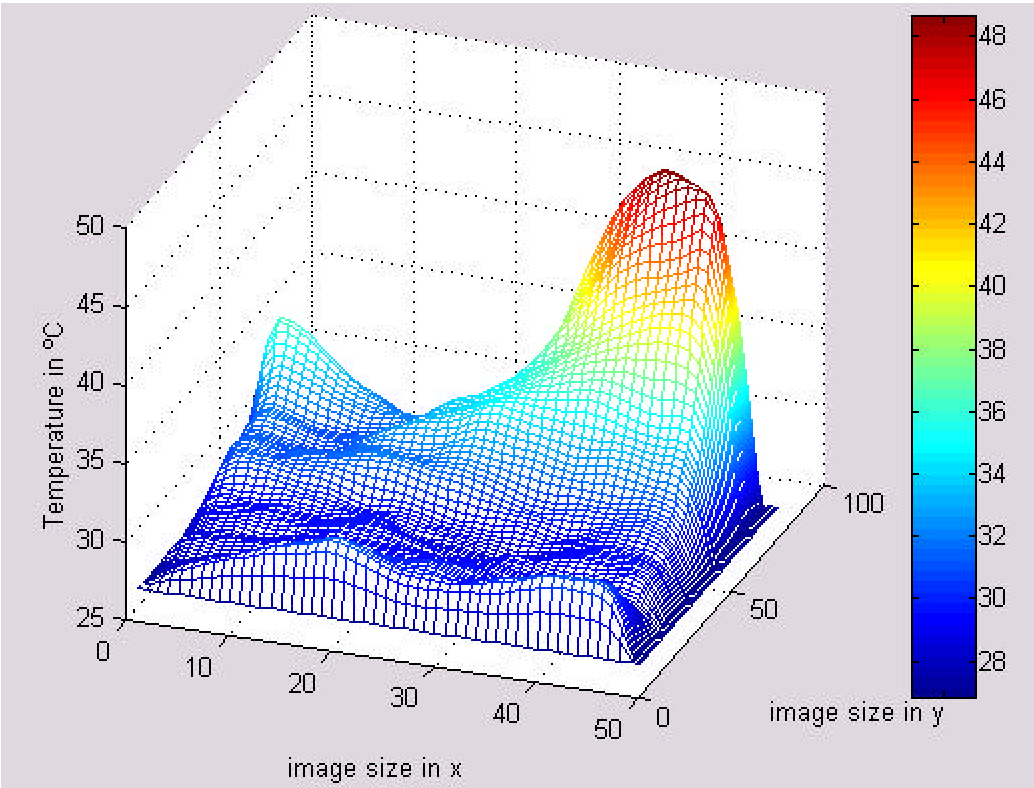

Figure 4 - TSP Measurement using TV apparatus

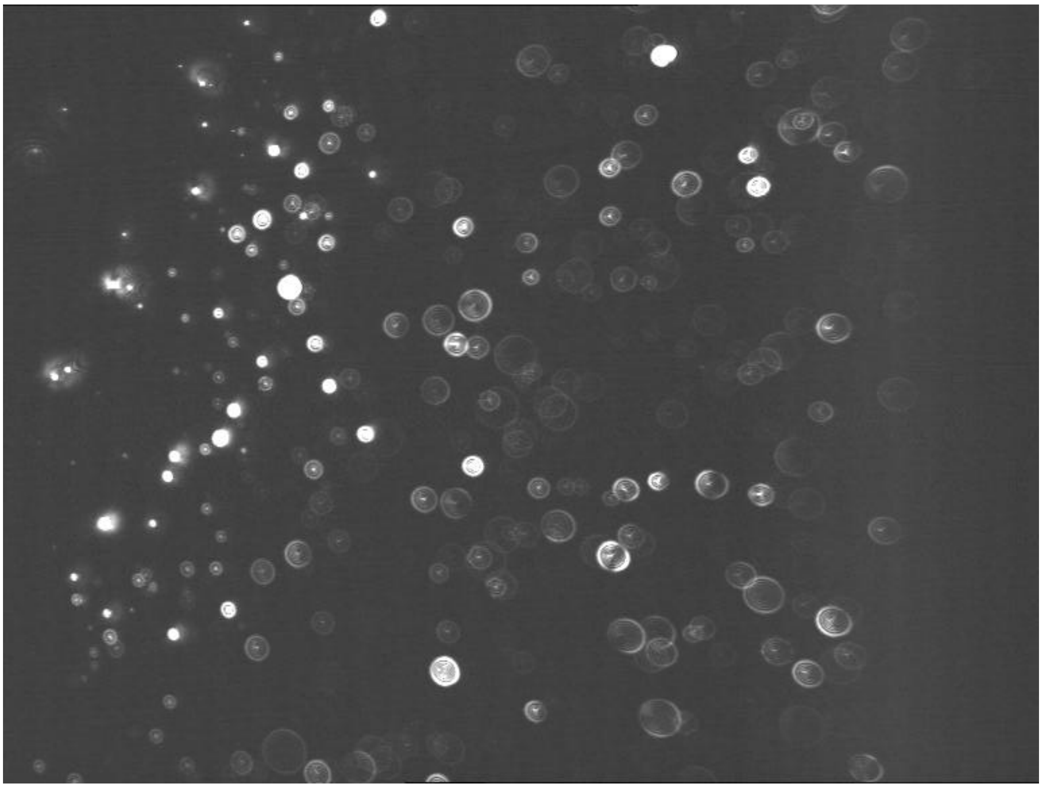

Figure 5 – Single-pulse Velocimetry data using TV technique (magnification: 1.2, particles: 1 μm polystyrene)

The technique can be extended to simultaneously measure velocity, density, viscosity (from which temperature can be deduced), and pressure. A mixture of three monodisperse-seeding particles are used to derive an estimate of density and viscosity as well as velocity. A marker seeding is chosen to follow the flow as closely as possible, while intermediate and large seeding populations provide two supplementary velocity fields, which are also dependent on fluid density and viscosity. A particle motion equation, is then solved over the whole field to provide both density and viscosity data. One way to separate the three velocity fields is to dye the different populations with fluorescent dyes. The combination of the three measured variables and the perfect-gas law leads to an estimate of the flow field thermodynamic pressure. Thus, the instantaneous state of a flow field can be completely described. This is the subject of current research to extend TV to be able to make all fluid variable measurements together with surface temperature/pressure. Current application of this method centres on the investigation of secondary flows in a two-stage turbine rig at a velocity of 0.5 Mach, to be reported elsewhere in the near future.

Finally, it is worth mentioning that it is well known that non-spherical particles exhibit a scattering field, which is very close to that of the equivalent spherical particle on-axis, but differ significantly for larger angles[17]. Therefore, this method can be used for high temperature seeding, such as stabilised alumina seeding, since high temperatures are not uncommon in subsonic and transonic flows, which are of particular interest in turbomachine component testing.

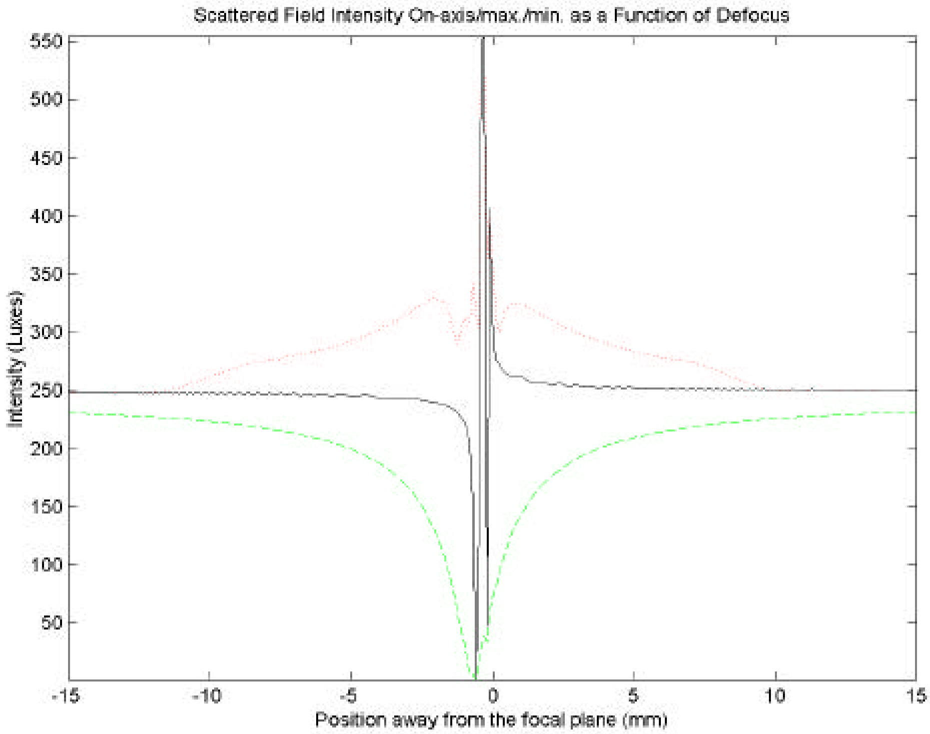

Figure 6 – Side View of particle scattering as a function of defocus.

Conclusion

Tunnelling Velocimetry has the following characteristics, which make it ideal for unsteady fluid flow studies:

- It is a volumetric method.
- It requires low to moderate illuminating powers, and so can potentially be used with high-repetition lasers.
- It requires a single optical access point.
- It can cope with arbitrary 3D velocity fields.
- It includes a PSP/TSP near-surface measurement capability.
- It is a robust method as it is contained within a single instrument.

In short, this technique exemplifies the definition of technology proposed by Adlai Stevenson[12] as "what happens when impossibility yields to necessity". 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. These results and those shown at the conference support the feasibility of the technique to make combined surface and fluid velocity measurements. Future work will include post-processing refinements, full fluid flow variable measurements and further particle scattering code development. Tunnelling velocimetry is being successfully developed to enable the four-variable investigation of fluids and their interactions with surfaces. This technique opens the way for the investigation of complex flow phenomena with high accuracy, using a robust and cost-effective means of measurement.

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