THE DEVELOPMENT OF A DOPPLER GLOBAL VELOCIMETER FOR TRANSONIC TURBINE APPLICATIONS

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ABSTRACT
The development of a Doppler Global Velocimeter (DGV) for the measurement of transonic turbo-machinery flows in the Oxford Isentropic Light Piston Tunnel rotor facility is described. A novel optical arrangement for capturing both reference and iodine cell discriminated images with a single CCD camera and frame grabber is presented. Practical arrangements for determination of the iodine cell transmission properties as a function of temperature and light frequency are discussed in the context of using an argon ion continuous wave laser for illumination. Flow seeding aspects of the experiment are described with particular emphasis on particle dynamics and light scattering. Error bounds for the DGV measurements are assessed and quantified in respect to the frame grabber resolution and Gaussian beam profile. Results of measurements of the velocity of a rotating disc with tip speed of nominally 90 m/s, obtained with 0.5 W single mode argon ion laser illumination are presented. Practical aspects for employing the DGV on the established Oxford rotor facility, such as seeding of the flow, optical access and synchronisation of data acquisition are addressed.

INTRODUCTION
The design of a gas turbine engine with higher specific thrust and better overall fuel consumption relies, at least in part, on a thorough understanding of the thermo-fluid dynamic phenomena occurring within the engine passages. The difficulty of measuring such flows in hot turbine stages led to the commissioning in Oxford of a transient single stage turbine test facility that produces engine representative conditions for short periods of time (typically 200 ms). The facility comprises an isentropic light piston tunnel (ILPT), which has been conceived, developed and employed in Oxford for over 20 years, and a fully three dimensional turbine stage. A full description is given by Ainsworth et al (1988) and Sheard and Ainsworth (1990). Blade surface heat transfer measurements have been reported by Hilditch and Ainsworth (1990); blade surface pressure measurements by Ainsworth et al (1991) and Dietz and Ainsworth (1992).

The emergence of computational fluid dynamic codes (CFD) as a tool in the investigation of turbo-machinery flows has led to a density of numerical information beyond that currently available from the experimental data base. An example calculation of the 2-D instantaneous velocity distribution in the Oxford turbine stage, using the two dimensional unsteady code of Giles (1988), is shown in Figure 1. Such codes rely on comparison with experiment for verification purposes before any confidence can be attached to their implications. The measurement of typical turbo-machinery flows for code validation has thus become of prime importance to engine manufacturers.

Also of consequence in measuring flows in engine type geometries is the effect of aerodynamic probes on the local flow regime. Non-intrusive laser techniques such as laser Doppler anemometry (LDA) and laser dual focus (L2F) have been used in turbo-machinery type flows for a number of years (eg Wittig et al (1986), Fagan and Fleeter (1991)), but as with aerodynamic probes, these are point-wise techniques and as such require long periods of tunnel measurement.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$E_1$</td>
<td>Uncertainty in derived velocity</td>
</tr>
<tr>
<td>$I_1, I_2$</td>
<td>Signal and reference intensities</td>
</tr>
<tr>
<td>$L$</td>
<td>Iodine cell length</td>
</tr>
<tr>
<td>$T$</td>
<td>Iodine cell temperature</td>
</tr>
<tr>
<td>$T_{11}, T_{12}, T_{13}$</td>
<td>Transformation matrix components</td>
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<tr>
<td>$v$</td>
<td>Velocity vector</td>
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<tr>
<td>$c$</td>
<td>Speed of light</td>
</tr>
<tr>
<td>$\hat{a}$</td>
<td>Unit vector in laser propagation direction</td>
</tr>
<tr>
<td>$\hat{o}$</td>
<td>Unit vector in observation direction</td>
</tr>
<tr>
<td>$\Delta v$</td>
<td>Doppler shift frequency</td>
</tr>
<tr>
<td>$\varepsilon_1, \varepsilon_2, \varepsilon_3$</td>
<td>Uncertainties in measured velocities</td>
</tr>
<tr>
<td>$v_0$</td>
<td>Laser emission frequency</td>
</tr>
<tr>
<td>$v_r$</td>
<td>Frequency of peak iodine absorption</td>
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Appi
mate of vie
Oxford

Figure 1: 2-D Unsteady stator/rotor prediction for the Oxford rotor and approximate field of view in rotor facility

running, or high instrumentation density, to quantify fully the flow field. The use of such methods in a short duration facility is consequently limited. Attention has therefore been focused on non-intrusive global measurement techniques - techniques that provide information over an extended area at a sequence of points in time. Particle image velocimetry (PIV) has recently found application in transonic nozzle guide vane flows (Bryanston-Cross et al (1991)), but there are immense difficulties in imaging the sub-micron particles necessary to follow such accelerated three dimensional flows fields. Holography has been applied to unsteady annular cascade flows (Davies and Bryanston-Cross (1984)), but such results are more qualitative than quantitative. The reporting of a new whole field, three component, velocimetry technique, Doppler Global Velocimetry (DGV) by Komine et al (1991) has led to an effort in Oxford to develop the technique for application to transonic flows in general and to the engine representative rotor facility in particular. This programme is concentrating on argon ion lasers for initial development and will progress to pulse lasers for high speed flows - providing instantaneous 3 component profiles of velocity.

THE BASIC PRINCIPLE

DGV is a technique that seeks to measure directly the Doppler shift in light frequency created by a moving object as it passes through a laser beam. The magnitude of this Doppler shift is related to the light propagation direction, \( \hat{i} \), the observation direction, \( \hat{o} \), the laser frequency, \( v \), and the object velocity vector \( \vec{V} \) by equation 1.

\[
\Delta v = v_o \frac{\hat{o} \cdot \hat{i}}{c} \cdot \vec{V}
\]  

This vector equation demonstrates that the Doppler shift is sensitive to one particular component of velocity, namely in the direction of \( \hat{o} - \hat{i} \), which is shown relative to the other vector quantities in Figure 2. This relation implies that the magnitude of the Doppler shift is a function of the observation direction, and consequently, three components of velocity can be derived on this basis.

Komine et al (1991) demonstrated the use of an iodine vapour cell as a tool in measuring Doppler shift frequencies over an extended two-dimensional area and introduced the nemonic of DGV. Iodine, like other halogens, has a plethora of absorption lines throughout the visible spectrum that are typically a few giga-hertz in width at room temperature. Some of these lines coincide with the frequency of emission of common lasers eg. the 514.5 nm emission of argon ion, the 532 nm emission of frequency doubled neodymium YAG laser. The laser light source for DGV measurements needs to have a narrow line width in comparison to the width of the iodine absorption feature. This is achieved in argon ion lasers by use of an inter-cavity etalon, and in Nd:YAG pulse lasers by use of injection seeding. By tuning the laser emission to the absorption

**Figure 2:** The measured velocity component relative to laser and observation directions for DGV

**Figure 3:** Frequency to intensity conversion principle of the DGV

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wing, changes in light frequency caused by moving objects can be converted into changes in light intensity by viewing the scattered light through an iodine vapour cell. Figure 3 shows a typical arrangement where the laser frequency is tuned to 50% transmission through the cell. For example, an argon ion laser operating at 514.5 nm can be tuned to coincide with this 50% point. If that light is incident upon a moving object, the scattered light is frequency shifted according to equation (1) and will therefore have a different level of transmission through the cell, i.e., less than or greater than 50% depending on the direction of object movement. These changes in frequency are also shown in Figure 4. Measurement of that change allows comparison with the known absorption curve to deduce the Doppler shift and hence object velocity. To measure velocity over an extended area, beam expanding optics are employed and an imaging system used to capture the scattered light. The method outlined thus far applies to any moving body that scatters light. To measure fluid velocities it is necessary to seed the flow with scattering sites in much the same way as is used in PIV, LDA and L2F. The laser beam is expanded using combinations of cylindrical lenses to provide a light sheet that illuminates a single plane of the flow - velocity measurements are obtained within this sheet.

To measure velocity quantitatively it is necessary to obtain two images of the same flow region, one viewed through the iodine cell, the other with no iodine cell, so that intensity variations across the imaged area can be normalised. Division of these two images on a pixel by pixel basis produces a two-dimensional map of iodine cell transmission over the viewed area - information that is related to the local Doppler shift via the cell calibration. Previous workers (Komine et al (1991)), Meyers and Komine (1991)) have reported the use of two separate CCD camera for the 'reference' and 'signal' images. Emphasis by these workers has been placed on obtaining and displaying real time velocity images in continuously running wind tunnels. For transient turbine simulation facilities such requirements are by-passed and consequently handling of the images can be carried out post-run.

The literature contains several applications of DGV to seeded flow fields. Komine and Brosnan (1991) carried out jet flow measurements while Meyers and Komine (1991) and Usry et al (1992) looked at the vortices above a delta wing at an angle of incidence to the free stream flow. The use of argon ion laser for time averaged results (averaged during the frame integration period of the CCD camera) and Nd:YAG pulse lasers for instantaneous (10 nSec flow illumination time) measurements are reported. The application of these lasers used an iodine cell as the frequency to intensity converting filter. The use of three separate imaging systems, which allows the determination of three velocity components has also been established (Komine et al (1991)). Signal processing schemes for the video data are treated by Meyers et al (1991).

The present programme will involve the application of DGV to flows in enclosed passages and within rotating turbo-machinery. The measurement of transonic flows, notoriously difficult with aerodynamic probes, will be addressed, as will the impact of various parameters on the accuracy obtained. In particular, the laser beam profile, frame grabber digitisation accuracy, CCD camera pixel noise and imaging system stability are areas of active interest.

PROPOSED IMAGING SYSTEM FOR TURBINE EXPERIMENTS

As outlined above, two fully synchronised images are required for each DGV measurement. Other workers, Komine et al (1991), Meyers and Komine (1991), have reported the use of two separate CCD cameras and electronics to obtain simultaneous frame integration between the two. This philosophy has enabled the capture and display of velocity fields in real time, but this is not an objective for the present study, where the final application being a short duration facility. The Oxford DGV system has therefore been designed to capture both reference and signal images using one CCD camera and one frame grabber.

Figure 4 shows a schematic diagram of the optical configuration. The decrease in electrical complexity compared to published methods, and the assurance of simultaneous image capture is at the expense of halving the potential spatial resolution of the measurement. This can be tolerated at present since the area of interest is relatively small (approximately 50mm square) and the DGV will yield approximately 200x200 pixels of data over this region. The primary lens shown in Figure 5 is used to capture and focus the scattered light into the back focal plane of a second lens, referred to as the transfer lens, which consequently outputs collimated light. The light is subsequently incident upon a beam splitter which separates the light between the reference and iodine cell paths. Mirrors guide the light toward a second beam splitter which acts to merge the two images into the CCD camera lens. The camera employed is a Sony XC77CE monochrome device. In this preliminary stage, frames are grabbed from this camera using a 6 bit frame grabber and image store which can retain up to 4 256x512 pixel images, although it is planned to move to higher resolution a-d in future. Data is then transferred to a workstation for analysis.

Spatial Alignment

As noted by other workers (Meyers and Komine (1991), Komine et al (1991)) the two images must be exactly aligned spatially, such
that there is an exact correspondence between pixels in the reference image and signal image. For the single camera technique this means that the reference image must be manipulated into the right hand portion of the CCD frame while the discriminated image is directed to the left portion. In this way corresponding pixels view exactly the same point in the object plane allowing division of the images on a pixel by pixel basis for comparison with the iodine absorption curve. The methodology chosen was to view test targets for coarse alignment and then to view point light sources to obtain precise alignment.

Signal Processing

In the manner expounded by other workers, the entire CCD plane is 'calibrated' such that variations in pixel sensitivity can be accounted for in the signal processing of the images. Details of the calibration are held on computer for use in the image processing algorithms. Each frame contains both reference and signal images which must first be extracted and removed following the alignment procedure of the previous section. The ratio on a pixel by pixel basis is then used with the iodine calibration to determine the Doppler shift relative to the measured laser frequency. Details of the geometrical layout of the experiment, also entered into the post-processing computer, allow these shifts to be converted into velocities via equation (1).

PARTICLE SEEDING OF FLOW FIELDS

The size of particle required to follow a strongly accelerated flow has been assessed by Hamed (1984), Patrick & Paterson (1981) et al amongst others. Hamed considered the particular case of particle trajectories through blade rows. The response of particles to changes in flow velocity and the ability of particles to follow turbulent fluctuations have been calculated by Melling & Whitelaw (1973). Bryanston-Cross & Epstein (1990) have looked at the particular case of transonic flows and the ability of particles to respond to step changes in velocity such as are found in shock waves.

For a particle to follow a normal shock change in velocity, with upstream Mach number 1.2, a particle of specific gravity 1 and on the order of 0.5 µm diameter is required. To follow 10 kHz turbulence to within 1 %, Melling & Whitelaw (1973) determined that a particle size of 0.8 µm and specific density 1 is required. The swirl velocity associated with turbo-machinery flows introduces the influence of a radial acceleration, although this has been shown, Melling & Whitelaw (1973), to have little impact. In conclusion, a target particle size of 0.5 µm and specific gravity 1 has been chosen.

The implications of particle dynamics cannot be considered in isolation. Not only must the particles follow the flow, they must also scatter sufficient light to enable detection. However, DGV is not reliant upon imaging individual scattering sites, as in reality each CCD pixel images a number of particles dependent on the seeding density and magnification of the imaging system. Nevertheless, particle scattering efficiency is critical in establishing the required laser power and seeding concentration. For particles on the order of 1 µm in diameter, light scattering is dictated by the Mie theory (see for example, van de Hulst (1957)). Extensive calculations based on this theory have been conducted in the current programme in order to assess the impact of particle size, refractive index and scattering angle.

Perhaps of greatest interest to DGV measurements is the effect of scattering angle, since this is a relatively free parameter when laying out the experiment. Figure 5 shows the effect of scattering angle for a particle diameter of 0.5 µm and refractive index of 1.4. Scattering is strongest in the forwards direction and reasonably strong in the side and back scatter directions. These forward and back scatter extremes are of little use to DGV measurements as viewing must occur at an oblique angle to the light sheet in order to provide global measurements. Two minima occur in the side scatter angles and could potentially have a deleterious consequence on the required illumination intensity and/or recording medium sensitivity.

Using this information the laser power and seeding concentration required for successful imaging of the flow field have been calculated for particular flow conditions. This involves assuming a certain illumination level within the light sheet and finding the seeding concentration necessary for a sufficient energy density to be incident upon the recording CCD element. Flexibility in matching the camera dynamic range to the variation in light intensity across the illuminated area is possible by use of apertures incorporated in the imaging system and by adjusting the laser power.

DETERMINATION OF THE IODINE CELL TRANSMISSION FUNCTION

Quantitative DGV measurements rely on an accurate knowledge of the iodine cell absorption profile as a function of light frequency in the region of the laser emission, see Figure 3. Facility has been incorporated into the DGV apparatus such that calibration of the cell, as a function of frequency and temperature, can be carried out quickly on site. The arrangement is shown schematically in Figure 6 for the case of an argon ion laser. This laser is fitted with a temperature stabilised etalon which allows only one longitudinal mode of the laser cavity to oscillate, thus enabling a narrow bandwidth output. Tuning of the laser frequency is achieved by varying the temperature of the etalon glass plate with a closed loop controller. The gain bandwidth of the green 514.5 nm argon

![Figure 5: The effect of scattering angle on light scattering power](image-url)

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emission is approximately 9 GHz, which covers two absorption peaks in the iodine cell. The frequency of the laser is monitored using a scanning Fabry-Perot (FP) interferometer with a 2 GHz free spectral range. The finesse of the device is in excess of 300, implying a resolution of 7 MHz. The scanning FP also allows verification of the single mode operation of the laser. Measurement of the iodine cell transmission function is accomplished in a near automatic manner by making the laser sweep across its gain bandwidth by altering the etalon temperature. FP data is periodically obtained using high speed analogue to digital converters to capture the piezo monitor voltage and amplified photodiode output, the data being stored in a personal computer. Simultaneously, the amplified outputs from the two photodiodes shown in Figure 6 are digitised and the ratio of these provides the cell transmission. Post processing of the data identifies the relative position of the FP spikes for each measurement, which are directly related to the laser output frequency. This information, coupled with the photodiode output ratio, provides the transmission function.

The scanning FP is mounted in a thermally stable environment so as to minimise temperature dependent drift in the mirror separation which can induce a drift of 100 MHz per degree C of ambient temperature rise. The stability is better than 1 degree C per hour. The temperature of the iodine cell is critical and must be maintained constant during the calibration procedure which takes approximately 10 minutes to complete. This is achieved by ensuring the cell has a high thermal inertia and employing closed loop temperature control.

Repetition of the procedure at a number of cell temperatures allows a map of absorption properties to be obtained. Figure 7 shows such a map for 60 mm path length cell. The absorption profiles are approximately Gaussian in shape and become progressively deeper as the temperature of the cell is increased. This increase in absorption can be predicted from the known vapour pressure curve of iodine, being directly related to the number density of gas phase iodine molecules. The width of the absorption feature is approximately 2 GHz and does not appreciably change over the range of temperatures considered. The linear portion of the wings show a sensitivity of around 10 MHz per % change in absorption.

This data is incorporated into the post processing algorithms that determine velocity from the acquired DGV images. The philosophy adopted has been to produce a DGV system which has an absolute calibration based on the measured properties of the laser and absorption cell. Other workers (Meyers and Komine (1991)) have described the use of a rotating disc to calibrate the system, but this is not considered by the present authors to be a practical proposition once an elaborate application has been constructed. A stable reference iodine cell has been developed which is used as a frequency standard to monitor the laser emission continuously. The transmission through the imaging system iodine cell, typically at a different temperature to the reference cell, can then be found from the experimentally determined transmission map.

THE PROPERTIES OF THE DGV LASER

As has already been explained, the laser source needs to be of narrow linewidth and tunable across an absorption feature of iodine. Also important is the stability of the laser output and in particular the ability to determine the laser frequency relative to the absorption feature during acquisition of the DGV images - Doppler shifts will be measured relative to the source frequency. The stability of the argon ion laser already discussed has therefore been investigated. This standard argon ion laser is characterised by two types of frequency fluctuation. The first is due to thermal effects causing the expansion and contraction of the resonator and consequently cavity mirror separation. The second is caused by vibrations which cause a more rapid oscillation in cavity mirror separation - water cooling flows are the main cause of this phenomena.

The first type of frequency modulation manifests itself as a slow drift of the output frequency between longitudinal resonant modes (separation of 140 MHz) and then a rapid 'mode hop' back to the original frequency. This type of feature is particularly pronounced during warm-up when the resonator is undergoing a temperature rise. After one hour of operation the period of these mode hops is several minutes, although still a strong function of ambient tem-
perature variations. A scanning FP can be used to monitor these modes graphically on an oscilloscope.

The second type of frequency modulation can be considered an ‘ac’ component superimposed on the first type. Investigation of this phenomena is more important as it occurs on a time scale comparable to the CCD camera frame integration period. Whereas the investigation of long time scale fluctuations used a scanning FP, higher frequency components have been quantified using a different technique. This latter method employs an iodine cell to act as a spectrum analyser. Consider again the shape of the iodine absorption feature shown in Figure 3. The side wings have a region which is linear over a region of approximately 600 MHz. By tuning the output into this region, say 50 % transmission, high frequency modulation of the laser output frequency is converted into a corresponding change in transmission through the cell. This transmission is monitored using photodiodes, as is done during the iodine cell calibration, and high speed a-d converters which simultaneously capture the reference and iodine cell intensities. From the iodine cell calibration, this data is used to deduce the level of frequency fluctuation in the laser output. Figure 8 shows the laser frequency fluctuations over short time scales found by this technique. Results indicate a 200 Hz oscillation in the output frequency with an amplitude of 10 MHz. In theory such variations are damaging to the accuracy of the DGV measurement since the variation in laser frequency may represent an error of up to +/- 5 m/s in velocity. However, by monitoring the laser frequency during the integration period of the camera, the effect of the changes can be accounted for when calculating the velocity.

The proposed use of a Nd:YAG pulse laser for instantaneous measurements will follow similar lines to those outlined in the bench scale argon ion tests. This device is fitted with an injection seeding system that controls the frequency output of the Q switched resonator. The injection seeder is a narrow linewidth solid state laser which is directed into the main cavity and causes the Nd:YAG pulse to build up at that frequency rather than from spontaneous noise. The overall linewidth is Fourier limited to approximately 90 MHz which is significantly broader than the single mode argon ion laser already discussed. The effect of this can be calibrated out of the system by monitoring the effective laser emission frequency with a reference iodine cell.

**Reference Iodine Cell**

A reference iodine cell is used to monitor the laser emission relative to the iodine absorption line, as already described in a previous section. Figure 6 shows the practical arrangement involved, using a beam sampler to divert a small proportion of the output beam through an iodine cell. Two photodiodes monitor the reference and iodine cell transmitted light intensities. The known temperature of the reference cell allows the laser frequency to be related to the DGV imaging system iodine cell which may be at a different temperature. This reference cell is also used for monitoring the laser output during the frame integration period.

**ACCURACY OF DGV SYSTEM IN TURBINE CONTEXT**

Significant errors in DGV results are primarily due to the low resolution analogue to digital converters found in video frame grabbers and pixel noise within the CCD elements. Further uncertainty can be created by variations in the laser frequency and temperature fluctuations in the iodine cell. Poor alignment of the reference and signal images can also impair accuracy. Variations in the laser frequency are monitored by the reference cell and temperature fluctuations are minimised by closed loop heating control.

Modern frame grabbers are commonly available with 8 bit (256 grey level) resolution - higher resolutions being impractical owing to the high pixel read-out rate (in excess of 10 MHz). The DGV methodology involves the division of two grey levels from corresponding pixels in the reference and signal images - if the light level is low, inaccuracies are amplified by this low resolution. Due to variations in seeding density and laser intensity across the light sheet, the local reference image grey level is a function of position within the image while the signal image is also influenced by the level of Doppler shift on transmission through the iodine cell. Consequently, DGV measurement uncertainty is dependent upon the local scattering intensity.

The signal to noise ratio of the video rate CCD camera used in this preliminary work is quoted as better than 50 dB, implying that the rms magnitude of pixel noise is 2.2 mV. The video signal black level is 0.3 V while the white level is 1.0 V. For an 8 bit frame grabber the grey level separation is 2.73 V whereas for a 6 bit device it is 10.9 mV. Consequently, a reasonable approximation is to assume the grey level ratio is given by the limits given in equation (2). There seems to be little point in using higher resolution frame grabbers without also increasing the signal to noise ratio of the CCD camera as the noise level could be larger than the grey level separation.

$$\frac{I_1 - 1}{I_2 + 1} < \text{Ratio} < \frac{I_1 + 1}{I_2 - 1}$$  \hspace{1cm} (2)

where $I_1$ and $I_2$ are the signal pixel intensity and reference pixel intensity respectively.

These bounds have been used to predict the likely variation of error due to the Gaussian nature of the illuminating light sheet. This property of the beam produces a variation of illumination intensity across the flow domain. For an assumed uniformly seeded flow Figure 9 shows the variation in velocity measurement accuracy.
across the light sheet for both 8 bit and 6 bit frame grabber resolution - also shown is the assumed Gaussian profile of the laser. It has been assumed that the signal image intensity is 50% of that of the reference image. The uncertainty is, as expected, lowest in the centre of the light sheet where the illumination is highest. The use of higher resolution a-d converters means that more of the light sheet area will produce results within given error bounds. The implication of these calculations is to try to make the illuminating beam into a top-hat profile or somehow improve the uniformity of the illumination. The philosophy adopted in this work has been to spatially filter the expanded beam so as to reject the outer wings of the profile, since they do not provide sufficient illumination for meaningful results and add to general background scattering.

Whilst the error bounds expounded so far are acceptable for initial studies of the DGV method, future refinements should aim to get higher digitisation resolution by the use of slow scan cameras and also reduce the level of pixel noise by adopting cooled CCD elements. The effect of seeding non-uniformity will also lead to larger errors where the seeding concentration is lowest. The Nd:YAG laser has a more top-hat spatial profile, which alleviates some of the illumination difficulties.

Variations in cell temperature can lead to large changes in the absorption properties of the iodine cell. For analytical purposes the iodine cell transmission can be approximated by equation (3).

\[
T = \exp \left( -\frac{(v - v_0)^2}{\sigma^2} \right) \left( \frac{K_0}{T} \exp \left( -\frac{-7186.4}{T} + 23.056 \right) \right)
\]  

where D and K are experimentally determined constants. Equation (4) takes into account the effect of temperature via the known vapour pressure of iodine, which is included empirically.

This allows an analysis of the error in measured Doppler shift frequency caused by iodine cell temperature uncertainty i.e. \( \frac{d(\Delta f)}{dT} \). A typical example shows that this is of the order of 20 MHz/K which in a typical DGV geometry (with sensitivity 2 MHz/s) is an uncertainty of 10 MHz. Stabilisation of the cell temperature to within 0.1 K has been achieved over a three hour period, providing an uncertainty of approximately 1 m/s.

The Oxford rotor facility allows optical access to 40 degrees of arc of the annulus. Viewing directions and their impact on measuring all three orthogonal velocity components have been addressed. The nature of the vector equation (1) is such that obtaining, directly, the three conventional velocity components (radial, tangential and axial) for a turbo-machine is impossible when access to the illuminated region is restricted, resulting in a compromise configuration which measures three non-orthogonal components. A geometrical transformation can then be derived from the known viewing directions which converts the measured velocity vectors into the conventional components (Komine and Brosnan, 1991). This process can lead to larger errors, particularly if the sensitivity to a particular conventional component is low. We can consider these errors for the case where the observation directions are at an angle \( \phi \) to the tangential plane and off axis angle \( \theta \). Propagation of the measured velocity component errors into the derived orthogonal components can then be expressed as shown by equation (4).

\[
E_1 = \left( T_1 x_1 + T_2 x_2 + T_3 x_3 \right)^{1/2}
\]  

For the case of \( x_1 = x_2 = x_3 \) and \( \phi = 55 \degree, \theta = 45 \degree \), \( E_1 \) is typically 2\( x_1 \). Hence uncertainties are typically doubled when converting to orthogonal components.

**SINGLE CAMERA IMAGING SYSTEM RESULTS**

Verification of the effectiveness and integrity of the single camera technique has been established using a simple test case. A rotating disc has been used to provide Doppler shifts, using illumination from the argon ion laser.

The disc has a radius of 65 mm and can be rotated at speeds up to 14000 rpm, which is equates to a tip speed of 95 m/s. The geometrical layout of the laser, disk and imaging system is shown.
Reference Iodine Cell

From Laser Beam Expansion Rotating Disk

Beam Splitter Measured Component

Imaging System

Figure 11: Schematic diagram of the layout in the rotating disc experiment

Figure 12: Grey level ratio map for the rotating disc experiment

Figure 13: Variation of grey level through centre of rotating disc (upper and lower error bounds shown as dotted lines)

in Figure 11 - the measured velocity component is also shown and lies at an angle of 67 degrees to the disk rotational axis. This geometry is such that the DGV is sensitised to the horizontal velocity of the disk. The laser beam is expanded using a single spherical lens and projected on to the disk. The signal and reference portions of the acquired image are separated and divided to provide the ratio map shown in Figure 12. The variation of light and dark shading is directly related to the disk horizontal velocity, and demonstrates the expected horizontal bands. Figure 12 shows a plot of grey level ratio along one pixel row which passes through the centre of the disk. As expected, the light from the top of the disk is frequency shifted so as to increase iodine cell transmission while that at the bottom is shifted so as to decrease transmission. In the centre of the disc, where the horizontal velocity is zero, the grey level ratio represents the iodine cell transmission for the unshifted laser frequency. Also shown in Figure 13 are the error bounds based on digitisation inaccuracies. For the 6 bit resolution used in this preliminary work, errors are significantly higher than would be tolerated in a flow measurement.

FUTURE WORK

The DGV results presented here were obtained using a continuous wave argon ion laser, and therefore represent velocities averaged over the integration period of the CCD camera velocities. The use of an existing injection seeded Nd:YAG laser, producing up to 200 mJ of 532nm radiation per pulse, will be developed along similar lines to the argon ion laser. This will allow frozen field images of the flow velocity to be obtained. Extensive investigations into the measurement of transonic flows with a DGV system based on this laser will be conducted.

The influence and reduction of reflections within wind tunnels in general, and the rotor facility in particular, will be investigated, as will methods of improving overall accuracy. The digitisation resolution and CCD pixel noise are particularly important parameters, and the feasibility of using slow-scan, cooled CCD elements and high resolution (16 bit) frame grabbers will be addressed.

The ultimate aim of this programme of work is to capture instantaneous 3 component velocity profiles of the flow within an engine representative turbine stage simulation facility. In particular, whole field measurements of the rotor/stator interaction region and convection of wakes through rotor passages. To achieve this, emphasis has been placed on the development of DGV for high speed flows with a consequent interest in particle dynamics, light scattering and laser power considerations. Application to the existing Oxford rotor facility has meant modification to the present instrumentation access. In particular, optical access to the areas of interest will be achieved by use of a Perspex cassette of nozzle guide vanes which can be rapidly removed from the working section for cleaning. This cassette allows optical access to: three full NGV passages; the rotor/stator gap; five rotor passages and approximately two axial chords downstream of the rotor. See Figure 1.

Facility for flow illumination will be provided by making use of hollow structural members, both upstream and downstream of the working section, fitted with turning mirrors. Seeding of the flow field will be achieved by priming the piston tube with appropriately
sized particles immediately prior to a run. During the subsequent tunnel operation, the air and seeding in the tube is compressed and forced through the working section. The concentration of seeding can easily be varied as required by adjusting the length of time the seeding generators fill the tube. Synchronisation of the Nd:YAG laser pulses with the imaging system will be achieved by use of asynchronous reset cameras, and triggering from the encoder presently fitted on the rotor shaft.

CONCLUSIONS

The development of a Doppler Global Velocimeter for a turbo-machinery simulation facility has been presented with preliminary results of the measurement of rotating disc velocity field. A novel imaging system has been described and its performance verified in conjunction with a 6 bit frame grabber. Practical methods of quantifying the parameters of the DGV have been outlined and an analysis of the source of errors presented. Finally, details of the future work necessary to employ the system on the existing Oxford rotor facility have been explained.

The DGV technique, though at an early stage of development, has the capability of providing global velocity measurements in transonic flows. The use of such a non-intrusive technique in turbo-machinery flows will provide invaluable information to engine manufacturers, and in particular a unique experimental database for comparison with state of the art CFD computations.

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