INTELLIGENT DIAGNOSTIC OPTICS FOR FLOW VISUALIZATION

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ABSTRACT

A review has been made of several current optical diagnostics used for flow visualization. The limitations and strengths of each technique have been described. A new type of intelligent diagnostic optic designed for making three-dimensional measurement of velocity in a gas turbine combustor is proposed. The diagnostic uses an in-line tomographic approach combined with correlation theory to spatially locate structure within the flow. A discussion has been made as to why some optical diagnostics have been more successful than others in their general application. The potential advantages of evolving new technology and the implications for future instrumentation are also discussed.

Keywords: Tomographic Optical flow Diagnostics

1. INTRODUCTION

For many years researchers have been investigating methods of quantitatively visualizing flows. The principle objective of this paper is to use the experience of the author coupled with knowledge of evolving technology to consider what we may expect from the next generation of Intelligent Diagnostic Optics. The term ‘intelligent’ has been used to describe how computers can both be used to retain ‘knowledge’ and be able use synthetic intelligence to make decisions on behalf of the operator.

One way of looking into the future is to first review the past. Optical instrumentation has moved from being a photographic static image based approach to becoming a real-time active diagnostic with a wide range of applications.

Over the past two decades a generation of optical diagnostics have been created and applied. With hindsight it is possible to understand why some methods have prospered and grown into accepted laboratory tools while others have remained bespoke specialist curios. There are usually two reasons for this, either the technology is not available to sustain the technique or the method it is too application dependant. It is also of interest to analyse what new knowledge is being created and what new technological advances in optics and computing may lead us to expect in the future.

Currently, the range of flow measurement techniques available to be used for fluid flow analysis can be divided into three categories: intrusive, based on physical probes introduced in the flow; partially intrusive, based on flow markers injected into the flow, and completely non-intrusive, based on the optical detection of light scattering properties of the flow. These techniques can be regarded as complementary, rather than exclusive.

In the first category, pressure and temperature probes and hot wire anemometers [1] are used to provide local, steady state measurements. However, they have the fundamental limitations of interfering with the measured flow and creating local disturbances, especially at high speeds. Optical techniques such as Laser Two Focus (L2F)[2], Laser Doppler Anemometry (LDA)[3], Doppler Global Velocimetry (DGV)[4] and Particle Image Velocimetry (PIV)[5] can be generally regarded as non-intrusive, since the size and concentration of the particles introduced in the flow as measurement aids is too small to change the flow behaviour. L2F and LDA are single point techniques and provide good statistics for the time-averaged data at that point. For this reason, the main drawback is that spatial turbulent structures and transient effects in the flow cannot be solved. Also, data acquisition can prove a lengthy process, difficult for transient rigs with short run-time and sparse seeding.

These drawbacks are overcome by PIV and DGV, which provide multi-point, instantaneous measurements. PIV combines whole-field visualization with the instantaneous capture of the data and is a robust technique for industrial environments. It is a non-intrusive measurement method, based on the optical detection and recording of light scattered by particulate flow markers. The spatial displacement between two images of the same marker captured at two well-defined moments in time relates to the local velocity of the flow.

Examples of totally non-intrusive technique are Interferometry[34] and Laser Induced Fluorescence (LIF)[6], which rely on the optical properties of the flow itself and are mostly used in combustion applications. Interferometric measurements are whole-field and two-dimensional. However, the method is very sensitive to any optical deformations of the light path, especially optical anisotropy, the movement or vibration of optical surfaces. LIF is a promising technique, with the potential to determine density, temperature and velocity from the fluorescent emission spectrum of the fluid molecules. It is mostly suited to flows in which the emission can be easily separated from the noise and its success is still dependent on the CCD (Charge Coupled Device) camera and laser technological advances.

Given the emerging technology it is interesting to consider what new or enhanced diagnostics might be possible. As we move toward more intelligent computers and optical diagnostic systems, the balance shifts from simply being able to make a measurement to that of making a detailed comparison with computational prediction. A further shift has occurred, in that it is expected that the technique is user friendly. This accommodates the average time a user stays with a particular experimental system, which both in University and industry has fallen.

If the knowledge and technical requirement associated with making a technique work is high or there is a specific skill dependency, it can have a short lifetime. For example one reason holography was not pursued as a test technique in the USA was that it was perceived to be highly operator sensitive and thus vulnerable to the more mobile American workforce. This can also be seen as why some institutes have been able to produce a high caliber of results. In these cases it is often the stability, continuity and consistent funding of the organisation, which has kept a critical skills, base intact.

A second reason is that some techniques are more bespoke than others when it comes to setting up. Initially the quality and stability of lasers was a major issue, then the ability to align the system. A major success of LDA is that it has been perceived as a ‘point and shoot technology’. There is a backlash to this in that often technological problems have been simplified in order to promote sales.

Thirdly it is always a surprise to realise that many of the simpler visualisation approaches such as shadowgraphy, Schlieren or focused Schlieren are not attempted simply because fewer people know how to apply them.

There are also some problems, which have yet to be solved using optical techniques. In particular the measurement within combustion still remains difficult. This is also the region where most manufacturers consider that greatest gains in efficiency are still to be made. Until recently, there was not the technology or computing power to extract the multispectral, complex, spatially and temporally incoherent data associated with the combustion process. It is also the area where the power generation industry sees the greatest efficiency and economic gains to be possible. Beyond this there are now new aspects of technology that make methods that have previously failed emerge, as successful diagnostics look more promising.

We are also moving into a time of high resolution, self-calibrating and synthetically intelligent optical diagnostic systems. Much of the experience and knowledge, which has made previous diagnostics possible, relied on person skills; can now be incorporated into the software of the instrument.

2. REVIEW OF CURRENT METHODS

The paper will now look at the fundamentals of some optical diagnostics with a view to considering how they may evolve and what new knowledge may be generated.

2.1 LASER DOPPLER ANEMOMETRY (L.D.A.)

Laser Doppler Anemometry is a non-intrusive optical technique for measuring the velocity of a fluid at a point. Since the first applications in turbomachinery[7] it has matured into a now well-established optical technique that is commonly used in industry.

Principle of operation

LDA allows up to three components of velocity to be measured at any one time over a small volume, the size of which is determined by the intersection of two or more beams of coherent light.

The interference of the intersecting beams generates a grid of light within the measurement volume through which a flow tracing particles can pass, as shown in figure(1).

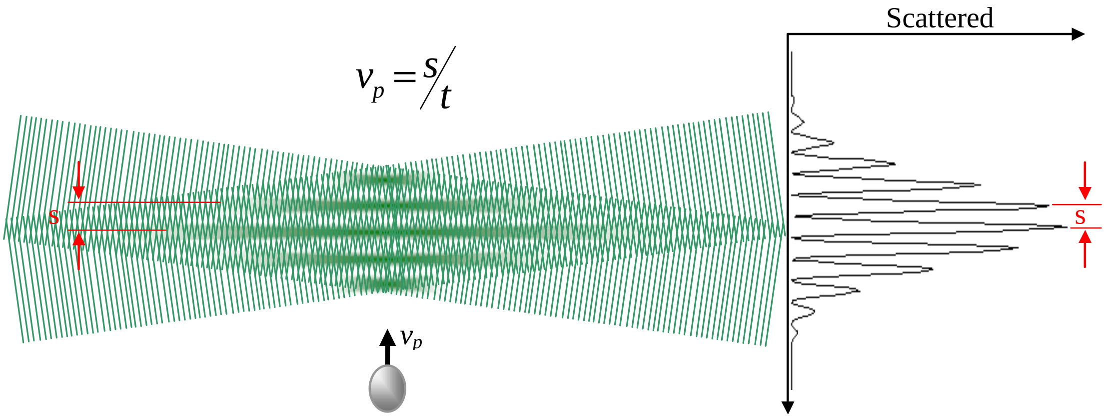


Figure 1. Fringe model. The intensity of the scattered light produced as a particle passes through a series of interference fringes contained within a measurement volume defined by the intersection of two coherent beams.

A typical measurement is made over an area of 200µm x 200µmm for a beam width of 50µm. The intensity of the light scattered by the particle as it passes through the

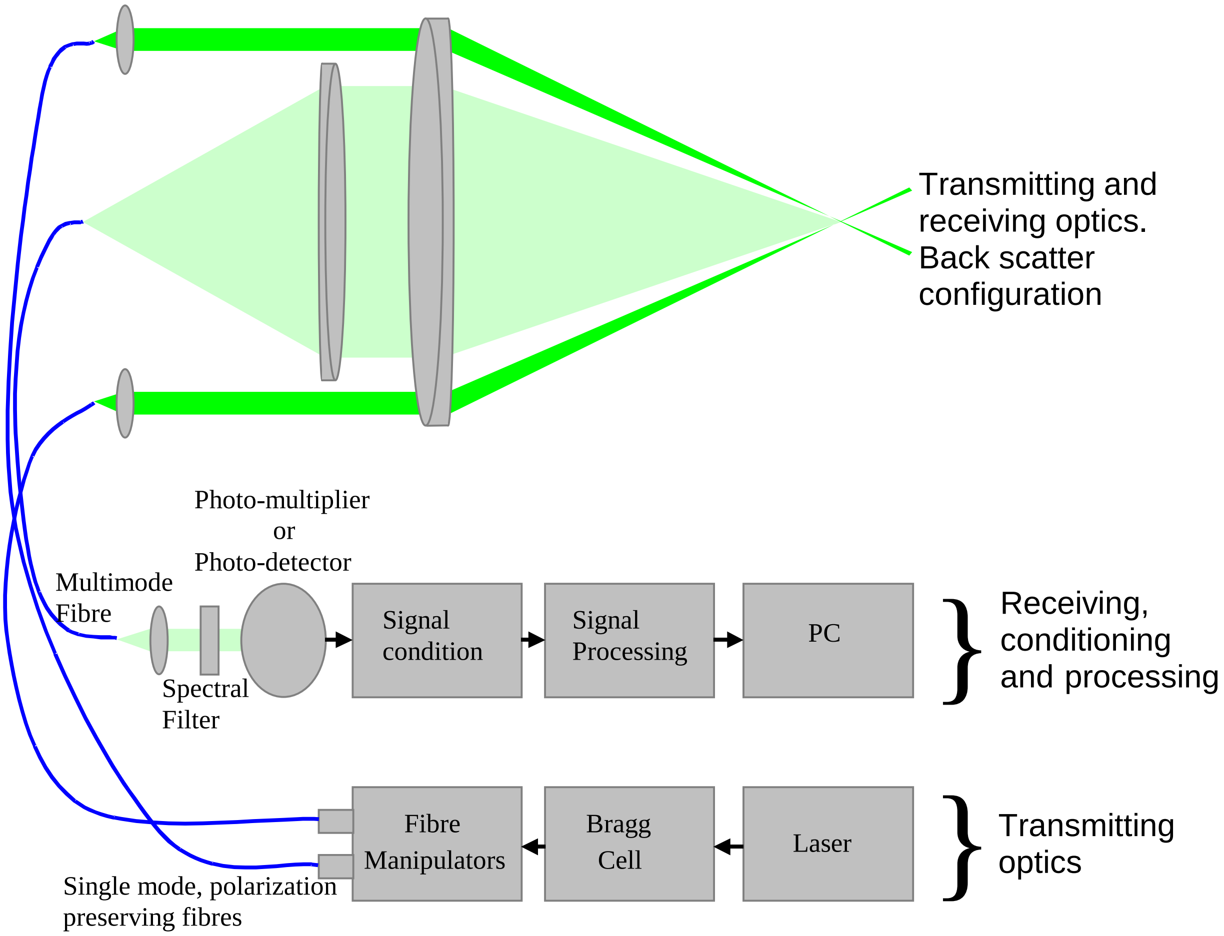


Figure 2. Laser Doppler Anemometer – backscatter configuration.

measurement volume is modulated according to the spacing of the fringes and the component of velocity of the particle normal to the plane of the fringes. The frequency of the pulses in the scattered intensity is equal to the velocity of the particle divided by the spacing of the fringes.

Figure (2) shows a schematic of a typical laser Doppler anemometer in the backscatter configuration. The anemometer consists of two sections, the transmitting and receiving systems respectively. The former consists of a coherent laser source, the beam of which is split and launched into polarisation maintaining single mode fibers that relay the beams to the launch head. Each of the emerging beams is collimated and focussed within the measurement volume.

With a measurement volume of dimensions of 50 microns the spatial resolution is potentially very good, although practically it can be limited by the long time periods required to traverse and map large areas. This is due to the time needed for sufficient particles to pass through the measurement volume to create a statistically significant measurement. The close proximity of surfaces, to within a millimeter of the center of the measurement volume, can mask the Doppler signal. Each of the channels must intersect within the same measurement volume to resolve the three dimensional vector of a single particle.

Accuracies range from ±2% to ±0.1% for prolonged acquisition periods in time invariant flows. Velocity ranges of less than $1ms^{-1}$ to hypersonic have been measured. In order to maintain a sufficient data rate there needs to be an abundance of seeding material. Data rates inevitably suffer in boundary layers or areas of recirculation. High refractive index gradients such as those found in flame fronts and boundary layers also present problems as do the use of curved or non-homogenous materials in the construction of the viewing window.

Current Development of the Instrument

LDA is conceptually very simple and highly portable. It has gained a wide acceptance as a measurement technique. However, in terms of the spatial temporal envelope it only provides a point measurement which is a temporal average of the data. To create a two or three-dimensional reconstruction measurement of the flow field requires a time intensive scan of the region of interest. The paradox of the technique is that the whole flow field can only be mapped, in detail accurately on a time-averaged basis by moving the interrogating spot from place to place. But in doing this is LDA can never provide an instantaneous mapping.

Figure (3) is an example of an LDA measurement of a transonic flow through the first stage compressor blade row of a gas turbine engine. Such detailed images often require long periods of expensive rig running with a cost of $5k/point, 400 points/plane and 20 planes/passage. The cost of mapping a commercial complex transonic first stage compressor flow is not inconsiderable. The results shown are of a compressor rotating at 10,000revs; with a peripheral blade time speed of 340km/s and a flow speed of 500 km/s. The image was provided by Rolls-Royce [8]. The particles being tracked through the rotor are of the order of 0.1µm. This type of measurement is used to validate numerical simulation, in an area which demands accuracy of the order of 2%. The results obtained have resulted in a important contribution to the design of the gas turbine engine [8].

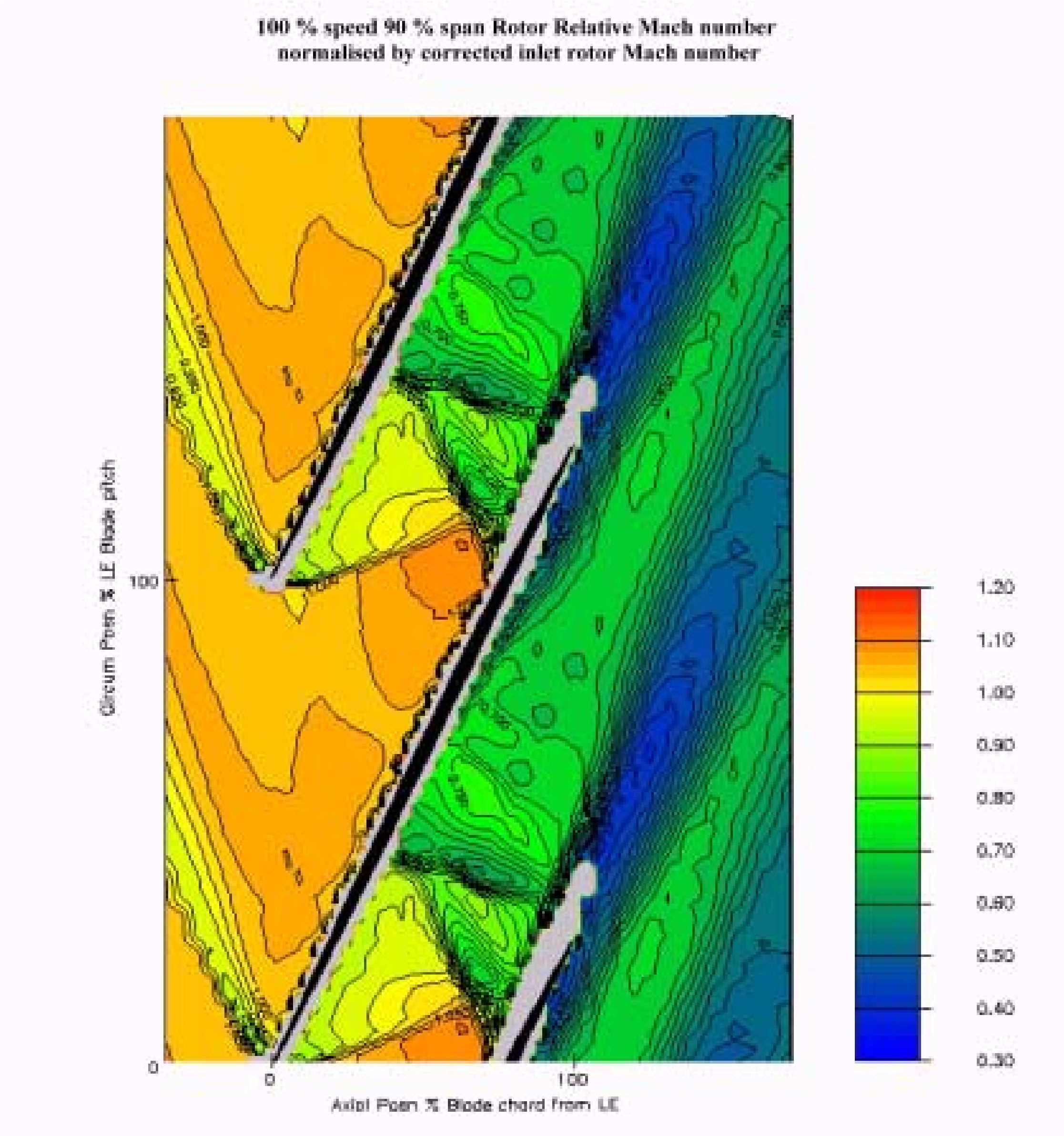


Figure 3. Plot showing the Velocity of the air passing through a rotating gas turbine compressor blade row made using LDA

There are other less obvious problems associated with such techniques. Firstly, the level of expertise needed to provide an intelligent result is substantial. There are also hidden layers of technological complexity, the operation of the laser and the critical launch of the beam into the fibres, which transmit the light through a lens into flow, are just two examples. A good understanding of the flow is also needed to set up the sampling window for the collection of the data. The interpretation of the statistic nature of the data, particularly in turbulent flows is also at challenging edge of the subject. A description of how the third component of velocity may be measured is given in [9]. A further more complex problem is what is meant by the turbulence level [10]. It can be difficult to differentiate between a genuinely turbulent flow and one that has intermittent coherent structures. The technique can provide accurate average values of turbulence but cannot be used to map the instantaneous bursting process as shown in figure (7) for example, within the boundary layer of low speed boundary layer flow. There is also the stamina needed to overcome the technical demands of long experimental data acquisition periods and the processing of complex three-dimensional data. The hard lesson seems to be the closer the researcher comes to the real problem, the more expensive and difficult it is to obtain a worthwhile measurement.

Finally, who uses the results and to what use are they put? Predictive codes have now become much more accurate and advanced over the past decade. In particular the unsteady three-dimensional nature of a transonic flow is now being predicted, Denton [11] and therefore there is a real need for a matching optical diagnostic accuracy. There is also a certain level of intelligence and experience needed to understand the fluid mechanics, interpret the measurement and the prediction to know how to use this information. Despite the complexity and difficulty of the instrumentation, the result of this approach has resulted in the designer being able to increase efficiency of the gas turbine engine by considerable amounts.

The Next Generation of LDA instrumentation

What can we expect in the evolution of this technique?

Firstly the cost of this type of instrumentation has not fallen. Although laser diodes and fibre optics make the LDA head a much neater package, the cost remains at the level of that associated with a specialized scientific instrument. What may be expected from current technology is that such an instrument be integrated with current control software. This could take the form of a self calibrating optical head, which would give a three dimensional display showing where it is within a defined CAD generated 3 dimensional map. The end result being an intelligent probe that has a ‘self’ positional awareness.

With the use of laser diodes and low weight diffraction limited optics it should be possible to create a computer controlled stepper motor which carries a light weight optical head allowing the operator to fly from point to point through the measurement space in a pre-configured sequence.

The use of high-powered diodes in a pulse mode of operation allows a further possibility. The particle could be first detected prior to entering the measurement volume. Then as it is in transit through the probe volume it could be illuminated a by high intensity laser pulse. This would make it possible to track smaller particles at higher speeds.

2.2 L2F (LASER TWO FOCUS) ANEMEOMETRY

L2F will only be mentioned briefly in this paper. It is an optical point measurement system similar to LDA, but projects two 250 microns spots into the flow field. A single particle breaking both spots creates a time of flight temporal signal. The intensity of the spots has allowed it to ‘see’ smaller particles than the LDA approach, however it is more vulnerable to turbulence in the flow. Greater precision allows improved spatial filtering of the signal to give a greater tolerance to surfaces adjacent to the probe volume. Schodl [12] also describes a three-dimensional two colour L2F system that has been packaged into a small rotatable optical head connected to a laser and photomultipliers via fibre optics, enabling 3 components to be measured from a narrow viewing angle. Schodl's work illustrates what can be achieved when a critical expertise is supported and pursued over a number of years. It is perhaps singularly the most influential work of its generation.

2.3 PARTICLE IMAGE VELOCIMETRY (PIV)

Principle of Operation

PIV (Particle Image Velocimetry) is a technique that has the potential to make an instantaneous velocity measurement of the whole flow field. In concept the technique is simple. It reduces the instantaneous measurement of the flow to an imaging process. A pulse laser is used as a high intensity (100mJ), short duration (10nsec) light source. The laser beam is shaped to form a narrow two-dimensional sheet of light (200µm). If the laser produces two, or more pulses, then images of a particle motion in the field can be stored.

Two-dimensional velocity measurements are made in a particle-laden flow. A double-pulsed laser sheet illuminates a two-dimensional particle field. An imaging device takes a picture of the double exposed individual particles. Given a known pulse separation and a measured particle image separation, velocity values across in the plane can be determined.

A representation of a PIV system is shown in figure(4).

Many publications have been made during the development of PIV. Examples of seminal work in this field can be attributed to Maynart [13] and Adrain [14]. Maynart demonstrated the strength of the method by mapping the particle distribution in a

Raleigh Bernard water-flow. A flow is also now being studied at the microscopic level using MicroPIV [15&16]. It has however, taken PIV many years to reach its current level of application. There are still significant data reduction problems to the application of PIV. It is a technique which has had to wait for both camera and computer technology to evolve in order to become useful measurement tool. It still badly needs the application of synthetic intelligence in order to make it into a ‘real’ time diagnostic.

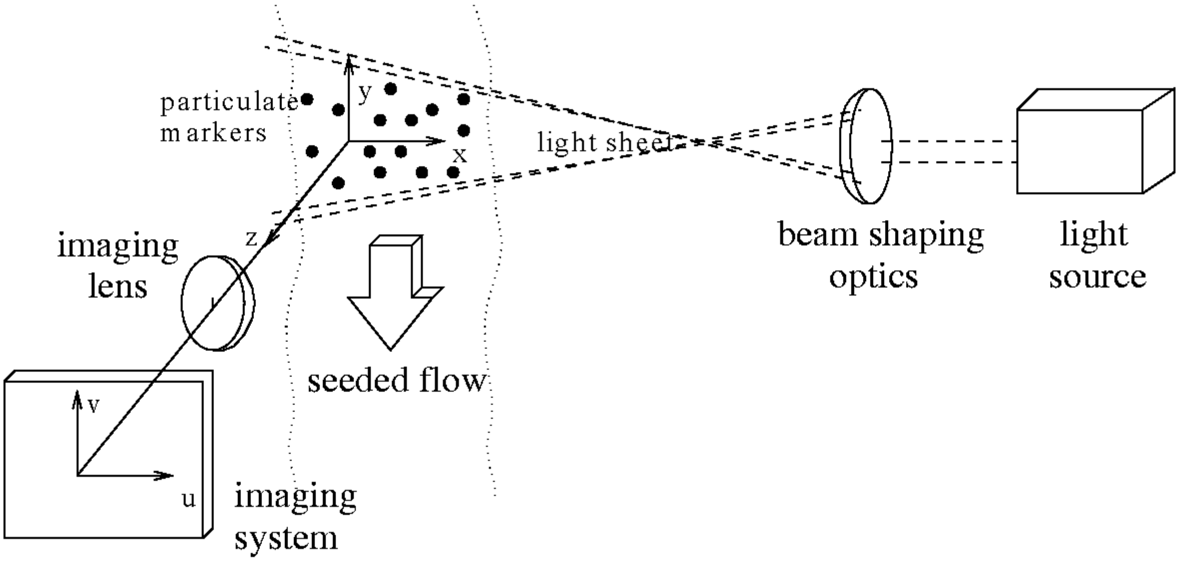


Figure 4. A schematic representation of a PIV system

From this simple combination there are now many variants.

Three-dimensional velocity measurements can be made using holographically stored particles, stereo cameras, single camera defocusing/diffraction and single camera aperture masks. [17]

Stereo camera configurations can also be used to study 3D flows. Notably by the applications of the Schiempflug condition [18].

PIV & Direct Flow Visualation: The Concept of a Comfortable test Environment.

In the experimental work completed for the automotive industry by the OEL [19], the primary drives have been to simplify the operation of the system to allow the designer to test their own models. As the concepts of ‘just in time’ and rapid prototyping have become established as manufacturing practice, then the speed and ease of concept to product designing has led to shorter design timescales. In the design of an engine block for example, the design cycle for building and testing using rapid prototyping methods is now 3 to 6 weeks. Thus the engine coolant flow diagnostics should be simple and quick to apply by the engineers themselves.

Thus it would seem right to provide a PIV/Visualisation approach which places the light sheet and camera under the total control of the test Engineer. The camera and image processing needs to be of sufficient quality, resolution and speed to provide a clear real time visualisation of the flow.

Using new miniature digital camera technology and a fibre optic based laser light sheet delivery are created from high resolution low weight diffraction based optics. The PIV system could provide a computer control system simple and light enough to be mounted on the arm of a low cost industrial robot.

This would allow the test engineer to fly through the transparent models, of their design, identifying and recording problem flow areas for modification. Detailed PIV measurement could then be made and evaluated directly with CFD calculation.

All diagnostics techniques have advantages and drawbacks, which balance complexity against accuracy. The underlining difficulty with PIV is accuracy and calibration. Aerodynamic measurements typically are to be made with an expected velocity resolution of 2%, achieving this over a large field of view in two or three dimensions requires demanding precision [20].

PIV is a technique that is highly dependent, at high speed, to the size of seeding particles used and the method used to launch them into the flow. Creating a suitably dense seeding concentration of particles, small enough to follow the flow is a serious consideration. Typically, in air, if the particles are greater than 0.2microns in diameter, there is a significant particle lag.

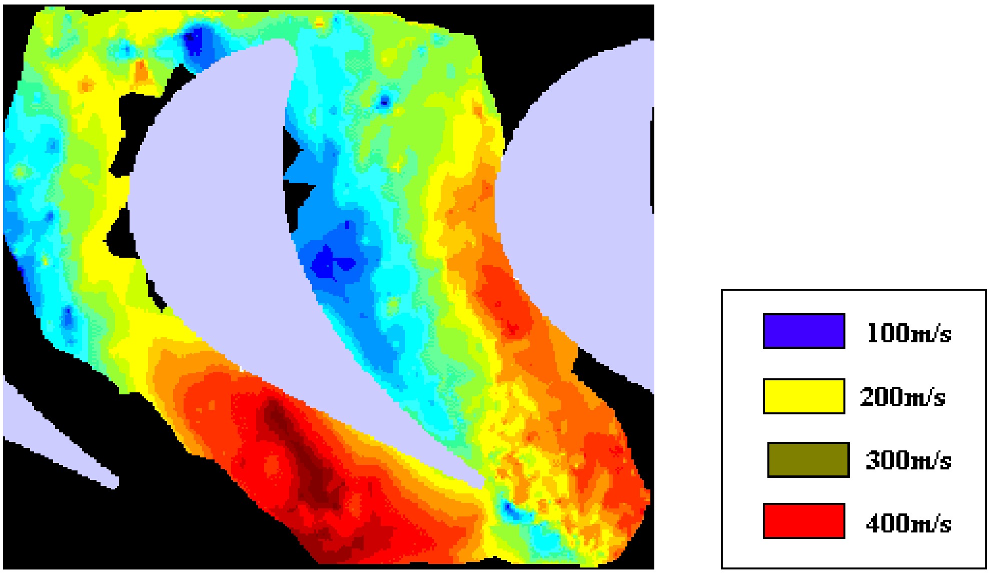


Figure 5. This figure is constructed from a PIV measurement made at MIT. It shows the air as it passes through a three-dimensional rotor spinning at 10,000revs.

Applications of PIV

The applications of PIV have grown rapidly. The images show two examples, the first is from a series of experiments performed upon a spinning transonic rotor [21]. This technique allowed the visualization of the instantaneous transonic flow in the inter-blade passage of a rotating annular cascade at engine conditions. By means of photographic recording of flow tracers and specialised image processing, the instantaneous velocity over the whole field was measured with estimated accuracy between 2 and 4%. The velocity contour map was created by using a Delaunay triangular grid.[20].

At the time of making this image the Nd/Yag laser used could only be run at 10Hz. The wake passing frequency in the transonic rotating flow is in the region of 5kHz. Thus although it is possible to see unsteady features in the image, they are only instantaneous snapshots, as shown in figure (6). A double firing laser capable of a pulse repetition rate of 10Khz is required to visualize the motion of the unsteady flow as it passes through the passage. Both the laser and the high-speed image intensified digital camera now exist making this measurement possible. Thus it is now technically possible to make an instantaneous unsteady flow measurement through a transonic blade row passage. An example of a low speed turbulent burst is shown in figure (7) and described in detail in [22].

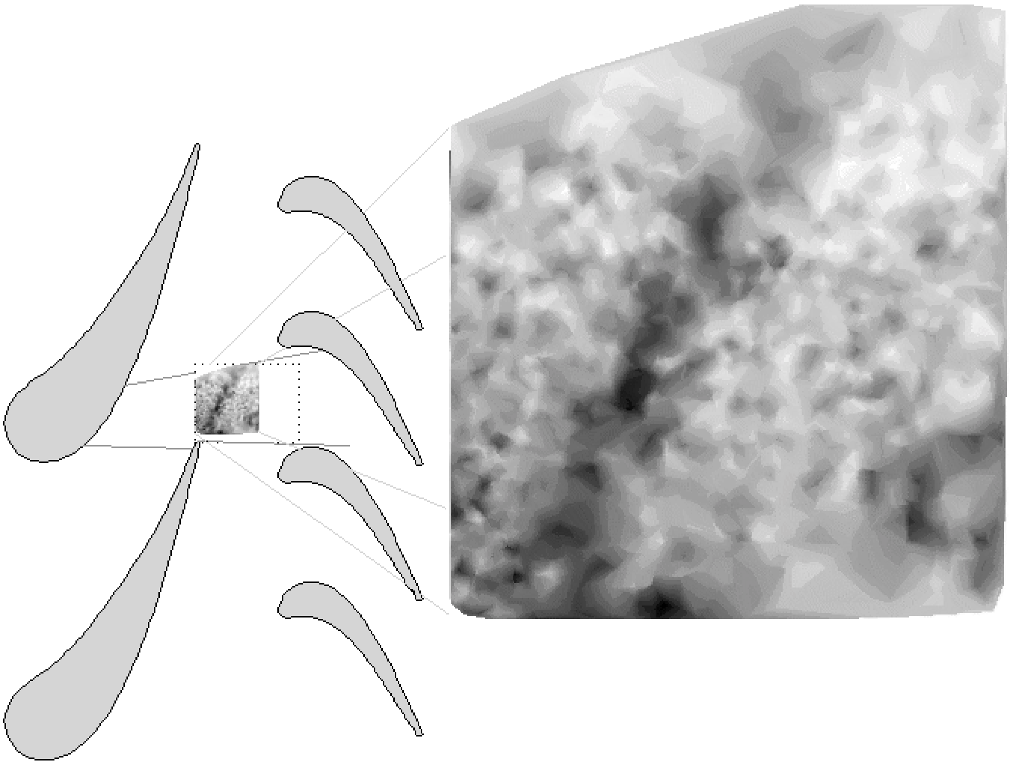


Figure 6. The stator wake. The image shows the wake from a stator blade as a dark slow moving region of fluid. There is a classic shed vortex structure which can also be seen in Fig(5). Other turbulent variations in velocity can be seen.

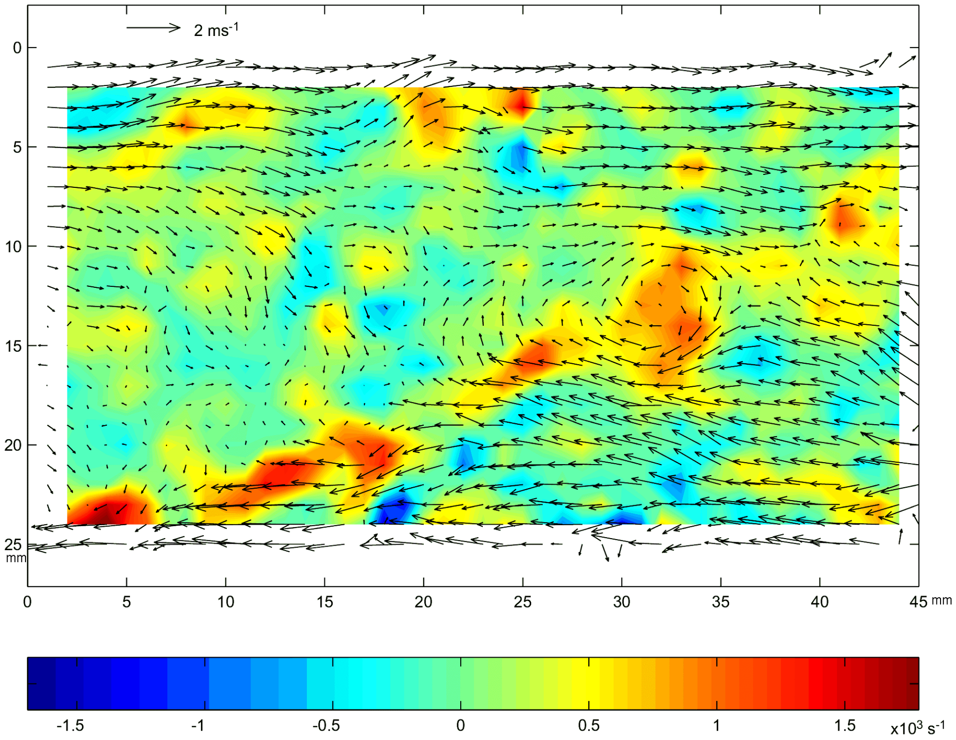


Figure 7. The image shows the bursting action of a vortex within the boundary layer of a slow moving air flow. In this image a filter has been applied to remove the boundary layer profile, reveling the bursting action.

Figure (8) shows the information that can be extracted. In this case the image has been processed using a specifically written Fourier filter. The filter has removed the high and low frequencies. The image shows details of the trailing edge wake at the rear of the turbine blade. A normal shock has also been visualised. These are two expected results but the filter has also exposed the existence of a passage vortex structure traveling through the blade row, created by an upstream stator blade. A PIV measurement would require the combination of a high repetition laser and a high speed image intensified digital camera to be able to track the progress of such a structure as it traveled through turbine row. It clearly also needs suitable automated image processing software to expose the details of the flow-field.

Figure 8. This shows three flow features visualized using an FFT filtering approach.

These being, the upstream wake, a weak transonic normal shock and the trailing edge wake at the bottom of the image. The image is a processed version of fig(5), again showing the turbulence rather than the steady state aspects of the flow.

The second example shown in figure(9) is the flow around two adjacent rotating cylinders.[23&24] For this novel flow configuration, the cylinders rotate in opposite directions with their outer surfaces in contact. Steady state tests were carried out for the following rotational Reynolds numbers, Re_{ϕ} = 75, 485, 966 and 1470.

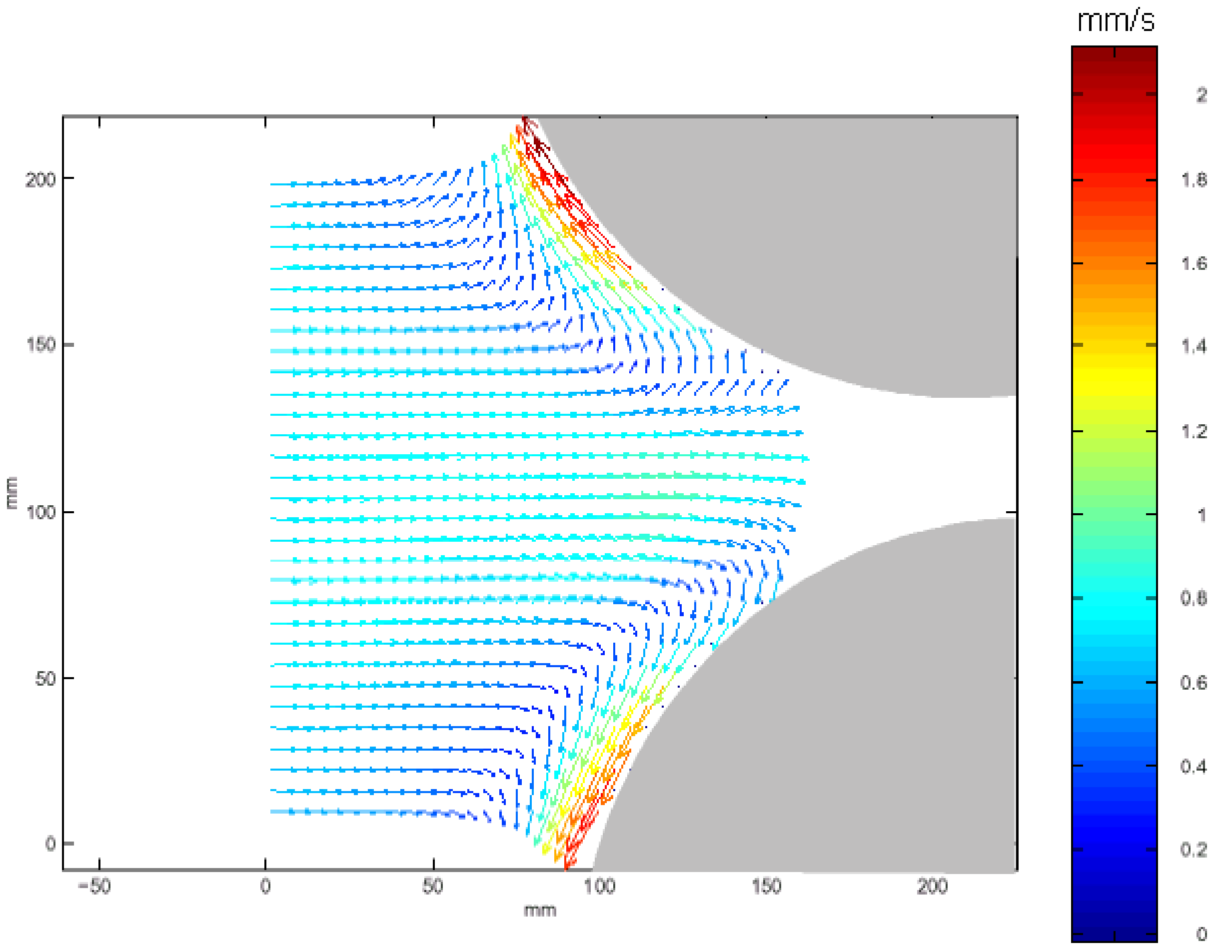


Figure 9. The figure shows a low speed flow between a pair of counter-rotating rollers

In both experiments the longest aspect of the work was the processing of the data, which has been processed using bespoke software. The software searched for individual particle images, found the center of each particle and then calculated the distance between possible pairs.[21] There is still a lack of available software to extract large scale image features from the processed image. It took 2 years to design and perform the data reduction required to both discriminate the signal to noise and particle cross-section and to augment the Delaunay grid software for the rotor image. The Delaunay grid, allows the plotting of irregular or sparse fields. In doing this velocity calculations can be made between grid point centers maintaining the accuracy of the calculation.[20]

The Future

The future for PIV is very promising. There is still a great deal to be done and much to come. The advent of high repetition Nd/Yag lasers and image intensifier cameras which can carry multiple CCD cameras makes it possible to consider being able to follow the high speed evolution of a turbulent structures, for example to be able to track the wake shed from an upstream rotor. A time series set images have been created by Westerweel [25] shows the transition from laminar to turbulence and the relaminisation of a boundary layer.

Perhaps the most evolutionary aspect is the use of synthetic intelligence in the creation of its PIV processing software [26]. The images shown in fig (5&9) were initially solved by ‘hand’ and took days to process. Using Fuzzy logic software it was found possible to solve the data in a few minutes. As the memory of computers increase and digital intensified cameras gain in resolution it will be possible to track complex flow events in real-time. However, the ability to track flow in 3D dimensions is still problematic. The use of stereo cameras appears at face value to be no more complex than that already achieved by LDA. However meeting for example the stereo camera requirements needed to meet the Scheimpflug condition needs very careful camera calibration. [16].

An experiment recently performed at MIT [27] showed that an image intensification of 200 was possible. Thus instead of requiring pulses of 100mJ, 0.5mJ would be sufficient. The same image enhanced digital camera also had a framing rate of 1MHz.

2.4 INTERFEROMETRY

The next techniques to be considered are Interferometry and Holographic Tomography.

Interferometry is a flow visualisation method that is non-intrusive and can give quantitative results concerning the density distribution in a compressible flow. No probes or seeding have to be placed in the flow and it can produce simultaneous information over the entire field. It is based on the retardation that a light ray experiences when crossing an in-homogenous refractive index (density) field.

The phase delay is proportional to a line integral of the density along the light path through the flow field. Once the phase delay is known the average density of the flow can be determined. The density distribution can then, using the isentropic flow equations, derive Mach number, as shown in fig (10). The image presented is a transonic flow through a two-dimensional gas turbine cascade and can be compared to that shown using PIV in figure (5). The information may be stored holographically, which allows the phase information to be post-processed. Holography has also been used to store three dimensional flow features such as those of transonic shock front. The image shown in Fig(11) shows the shockwave formed as an airflow enters the rotating first stage compressor fan of a gas turbine engine.[28]. Holography also allowed the use of low cost optical components in the formation of interferometric images.

Figure 11. Reconstruction of holographic image of the transonic flow within a compressor blade row.

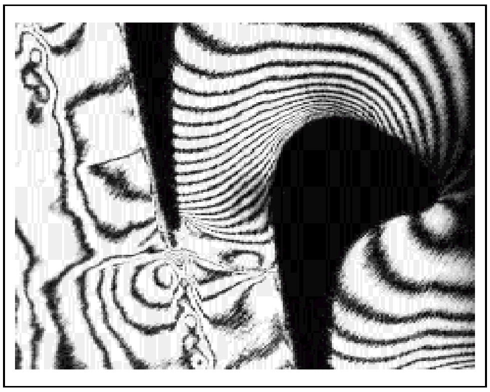


Figure 10. Interferogram of a transonic Flow through a 2-D turbine cascade.

As flow calculations [29] and experimental testing has moved from being two dimensional to three dimensional the value of such images, has shown in fig(10) is limited. Both Interferometry and Holography require both mechanical and laser (SLM, TEM_{00}) stability for beam splitting interferometers. This restraint is however, relaxed for beam shearing arrangements where the optical beams share common optical components and paths.

Holographic Tomography (HT)

To overcome the problems posed by trying to visualize three dimensional refractive index fields Vest [30] proposed the use of holographic tomography. This technique has been explored successfully by D.Watt [31], Soyoung Cha [32], S.Parker [33] and B.Timmerman [34]. It has a resulted in some spectacular results as shown by fig(12).

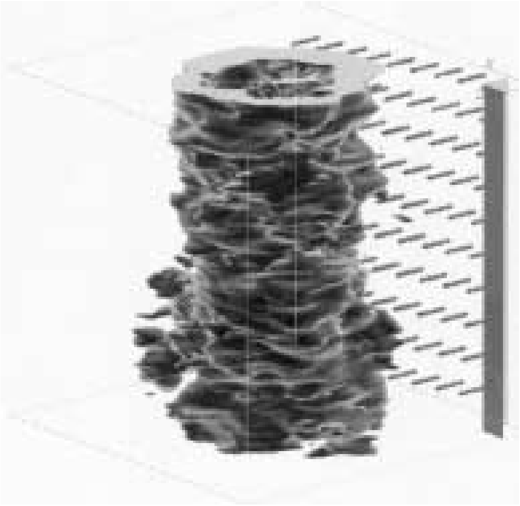


Figure 12. A tomographic reconstruction made from 8 holographic views. The image shows the turbulent structure of a high speed jet flow.

In essence it combines multiple interferometric views through the flow to create a three-dimensional phase and hence density map. However, the experimental system demands a wide angle of view and a complex experimental construction. This is coupled with a priori assumptions essential to reconstructing three dimensional refractive index fields. However, if the complexities of the system were embedded into the software and hardware of the digital cameras used, making the system ‘intelligent and self-aware’, the technique may yet emerge from its current restricted laboratory use. Currently as a technique it is not widely accepted and not made the contribution to fluid dynamics that, for example LDA has obviously done.

Attempts have been made to create in-line tomographic approaches, notably: amongst others by Fomin [35]. Here the direct relationship between refractive index bending and the projected speckle pattern has been used to create 3D image of the fluid. The technique however, requires assumptive arguments about the turbulent structure of the flow that does overcome the need for a wide viewing angle. Thus, HT at the moment is a technique that has yet to realize its potential as an optical diagnostic.

3. A CORRELATION BASED OPTICAL IN-LINE TOMOGRAPHIC DIAGNOSTIC FOR COMBUSTION

The following is a postulation of how the previously described techniques can be combined using current technology to create an instrument.

In-Line Optical Tomography

Work in the 70’s by Jakeman and Pike [36] explored how correlation approaches could be used to track large-scale flow features. This paper now proposes to look at how the three previous techniques described could now be combined into the operation of a new type of instrument. Instruments that can operate in a combusting flow and provide quantitative results.

Optical Filtering of the Combustion Flame

It has been shown that in several important combustion flows the existence of OH is significant indicator of the efficiency of the burning process. OH is formed in the intermolecular burning region. [37]. Because of its short lifetime, OH only exists in the 'skin' of the burning cell forming a layer between the burnt and unburnt gas. The images show, figure (13a), is a water flow simulation of the intermolecular mixing region between the air and fuel mixing process a fluorescent marker has been added to one of the flows. With the use of acid and base suppressants, the total intensity of the emitted light from a fluorescent marker [38] is only restricted to the molecular mixing region. A simulation of this has been achieved in figure (13b) by edge enhancing the image. If the OH line can be used in this manner, then the problem of tracking the

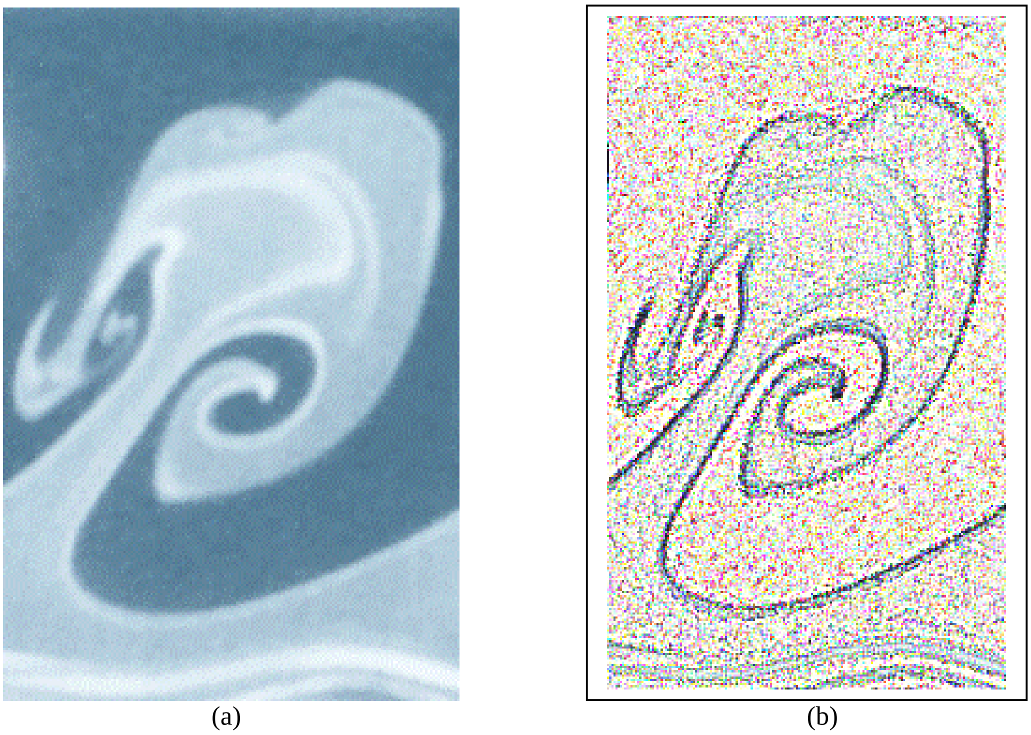
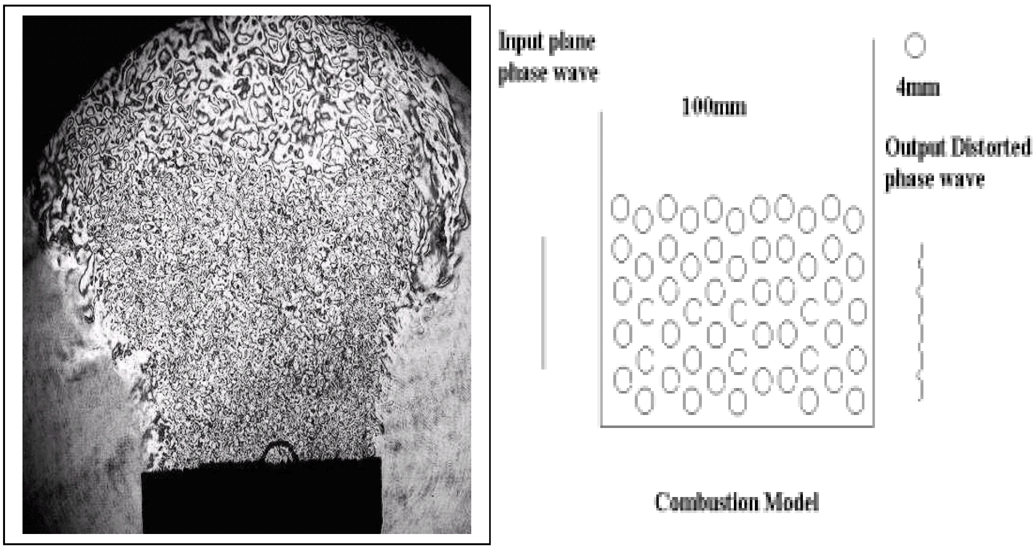

(a) (b)

Figure 13. (a) Shows a simulation of the mixing between two fluids and (b) This is an imaged processed version of (a) to shown the edge structure.

combustion flame has been reduced optically to that of tracking the light intensity being emitted from a complex bubble image structure.

Use of the Random Temporal Behavior of Turbulent Burning Structures

The image shown in figure (14a) shows a 0.1m diameter atmospheric 1000^{o}C burning propane gas jet made using holographic interferometry [39&40]. The work was performed to investigate the burning cell size as a function of induced swirl. The cell size measured from the interferogram is typically 4mm. There are several flow features of interest visualized in the inteferometric image. This phase image of the flame shows that there is little refractive index bending present. A theoretical model shown in figure (14b) of the flame shows that although the density gradients are high, the amount of bending is small due to the size and random nature of the burning cells. The cells also change in size and structure with distance from the burner. Finally, there is a characteristic chaotic structure to the flame.



(a) (b)

Figure 14. (a) Interferometric image of a propane flame and (b) Theoretical model of the combustion flame

In-Line Tomographic Imaging

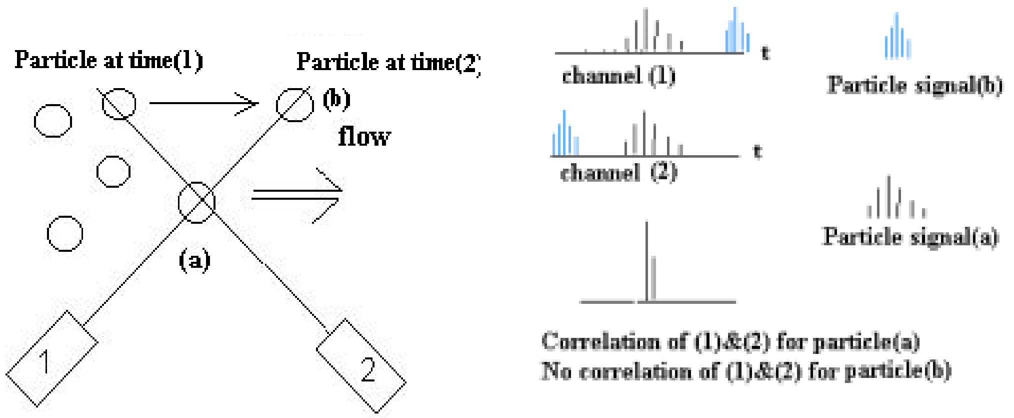
Provided the combustion field can be described as being constituted from turbulent structures or irregular shapes moving within the flow, it should be possible to retrieve their location in three dimensions by using their irregular structure. In principle only two optical projections, are needed to achieve this, as shown in figure (15).

Imagine the irregular structures consisting of an OH skin, which emits light at a specific wavelength. This example is based on combustion flames, where OH exists only in the molecular mixing region of the flame.

With these OH structures traveling in the field, the signal that is emitted from a single point will consist of pulses of light, as the OH edges pass. The timing between two pulses and strength will depend on the shape or strength of a specific structure.

Using two detectors, at a slight angle to each other, a correlation between the two signals can be made, from which the velocity of the structure can be derived. This approach is similar to the velocity correlation applied to particles passing through the measurement volume in an LDA system.

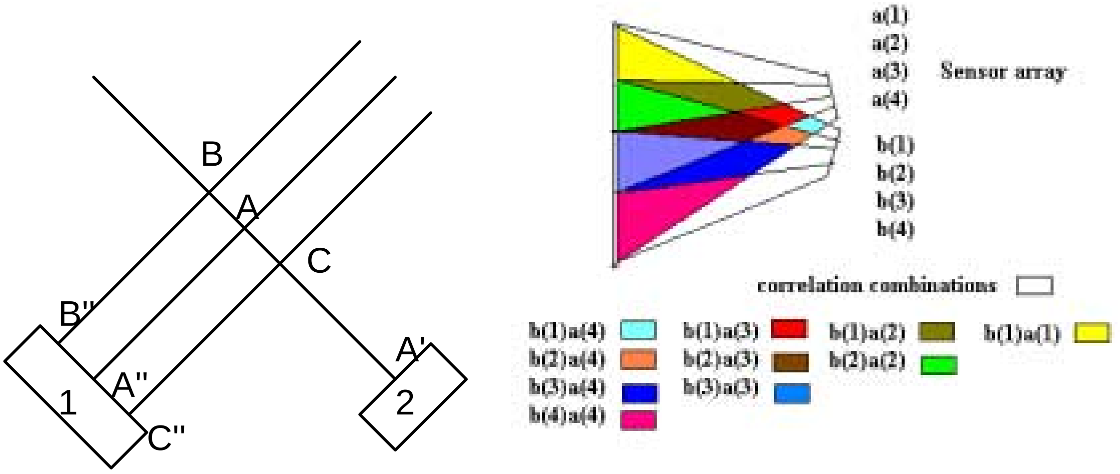
Imagine two detectors that have a viewing line that crosses at a certain point, shown in figure(15). An OH structure passing through that point will send a signal to both detectors. Each detector will receive signals from all other points along its respective line-of-sight, but only for the overlapping viewing area (point) will they find a correlating signal, This correlation result will occur provided the field is sufficiently incoherent. The time delay between the arrival at the two detectors is also shown in figure (15).



Particle(a) Particle(b)

Figure(15) The two plots show different signals. Particle (a) appears in channels(1)&(2) simultaneously. Particle (b) appears in channel (2) before it appears in channel (1), hence there will be no correlation.

Using a line array in detector 1 and a point detector in 2 the structures can be monitored along a line. Using line arrays in both detectors, the emission can be monitored from a two-dimensional field to locate each signal, the specific correlation signal from each point is used. This is similar to the ideas used in optical coherence tomography, or time-of-flight measurements, where use is made of light sources with a short coherence



(a) (b)

Figure 15. (a) Two line detectors imaging a 2-D field and (b) shows the area which correlate if two detectors with 4 sensors.

length to determine the spatial location of a signal.

However, there are many questions with respect to this proposed approach, which have yet to be explored experimentally:

> What resolution from the signal?
>
> What is the optimal angle between the sensors?
>
> Is the mathematical description of the 'bubble' model valid?
>
> How incoherent is the turbulent structure and what value of correlation can be achieved from this type of signal processing?
>
> Over what length of time will it necessary to sample the signal for to achieve a significant correlation coefficient?
>
> How sensitive is this technique for 'noise'/small signals?
>
> 1/R: Imagine two flames, one behind the other. The rear flame will give a weaker signal to each sensor at the detector, but on the other hand will be collected over a larger sold angle and thus reach more sensors than the flame closest to the detector.
>
> What percentage of the OH is re-absorbed as it passed through other flame centers?

This experimental approach was initially developed to investigate vortex bursting within a supersonic boundary layer. The study showed that because the shape of the bursting vortex changes very quickly an optical correlation of the shape was only possible for length scale of approximately one boundary layer thickness. In this case the boundary layer thickness was 5mm, a co-incidentally similar size to the expected size of the turbulent combustion cells [41&42]. Recent work by M.L.G.Oldfield [43], shows how the downstream turbulent pressure distribution structure of gas turbine combustor changes little between the burning and non-burning cases. It would be of interest to use the proposed probe to make similar length scale measurements within the combustor itself.

The proposed instrument could be used to locate a volume spatially by forming a temporal cross-correlation product in the image planes of the lenses. If this is the case, it should also be possible to measure the local heat release within the combustor.

If the individual turbulent structure of each cell gives it a local coherence, then, just as fig (15) shows a two dimensional object being mapped onto a one dimensional array, a three dimensional image could then be mapped onto a low-resolution two dimensional array. The turbulent features are low resolution, typically 1mm scale would seem adequate for mapping onto two probes of 100 x100 sensors.

To describe this in another way, in a holographic image 3D information of the object is phase encoded into a suitably high resolution storage material. In the combustion model case, the low-resolution incoherent temporal turbulence data is being used to encode spatial position using two low-resolution areas detectors. Cross correlation between these detectors localizes the position of the incoherent source. The intensity of the correlation may also related to the heat release from this structure.

Large scale PIV

So far the operation of this instrument is similar to that used to develop this initial correlators used originally in LDA and L2F systems and reviewed at the start of this paper. At that time the technology limited what could considered to be a single dimensional correlator. It is now possible using the area array devices to collect the turbulent data structure in three dimensions.

Once the essential structural mapping of the volume has been completed the data resembles that of large particles traveling within a fluid. By using a combination of correlation theory and particle tracking the passage of the structure can be mapped in 3D as it travels through the fluid. If, for example, a time delay corresponding the transit time for particle (b) in figure (15) were added to channel (2) then a positive correlation would be achieved, as shown in figure (17).

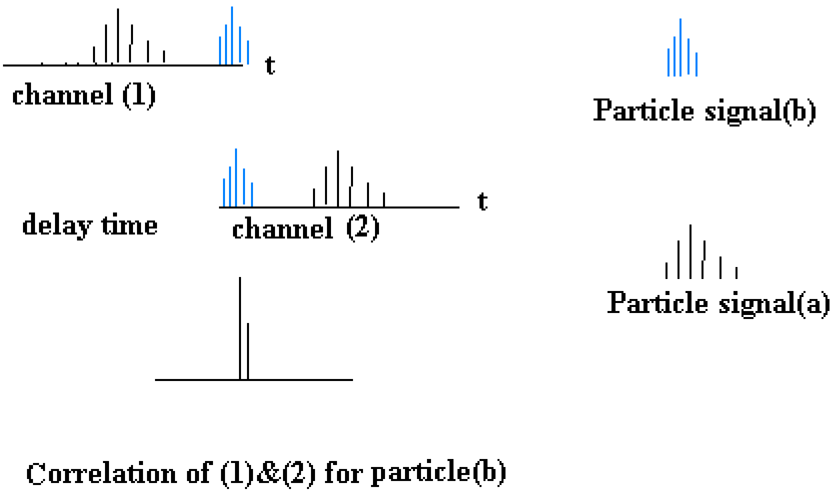


Figure (17) Channel (2) has been delayed to provide a correlation for particle (b).

This is exactly how the PIV data in the previous examples shown in figures (5,6,7&9) were processed. Thus there is the potential using this approach to extract the 3D velocity field within the combustion zone. Previous work [42] demonstrates that the short-lived semi-coherent signature of a turbulence structure can be velocity tracked in this manner.

4. CONCLUSIONS

In the main the most effective method of visualization, when it is possible, is the simplest. The most useful diagnostic tests in industry performed by the OEL have been achieved when the system is simple enough for the designer to be able to control the test and see the results directly. They understand the flow and are most likely to achieve the most effective result quickest. In the case of low speed coolant flows through an automotive engine; it has been possible for the designer to track the flow feature of interest. 90% of the diagnostic knowledge has been gained in this manner. PIV has often been performed as an afterthought for numerical comparison with CFD.

Thus, a video camera mounted orthogonal to a fibre optics projected laser light sheet can visualise a large number of flows. Using the current technology of near photographic resolution digital cameras assists the resolution and accuracy with which such measurements can be made. This added to a high speed an electronic imaging camera the systems moves quickly to being able to visualise high-speed flows. What has been lacking until recently has the ability to provide substantial software for extracting information from the images. NASA’s pioneering work in this field shows that the route by which fuzzy logic, neural networks and genetic algorithms can simplify images that would have previously been impenetrable. Finally by creating a flexible joystick control the user could ‘fly’ through the flow. In such a way, it now becomes possible to see how a product design team would use such a device for the rapid development and evaluation of flow models. It also essential to present data in a suitably digestible manner.

The time between product design and manufacture in almost all industries has fallen significantly. In the automotive industry it is essential to provide a result within a 6-week design time cycle. Also the rate at which staff move position has increased, certainly to less than a 3 year cycle. Simply the next generation of optical diagnostics should be simple, well packaged and with a great deal of synthetic intelligence programmed into them.

What seems to make a particular optical diagnostic successful is the users perception of simplicity of operation, portability and the direct and clear presentation of information. The diagnostic may be highly technologically complex, but progressively the requirement is to package this to be hidden within the instrument. It is also now to create low cost, lightweight, diffraction limited high quality optics. This coupled with high-resolution compact digital cameras could mean that the next generation to resemble type of diagnostic tools emerging for medical application.

The aero companies are using optical technology less in their aerodynamic investigations. As their understanding and numerical predictive ability has grown in confidence, the optical techniques have migrated to more fundamental areas of research, such as combustion. As the efficiencies to be gained from aerodynamic improvement have decreased the cost effectiveness of optical diagnostics has made them less attractive.

This argument favors direct visualization methods such as, PIV & LIF, which have a strong potential for development. In these case one can foresee that the designer may be able to pre-programme their inspection sequence and the type of flow features they wish to follow at the same time they commit the CAD model for rapid prototyping.

It would seem likely; particularly with the now limited supply of holographic materials that HT will move to be a wholly electronic imaging technique. Again using lightweight low cost directly phase sensitive digital cameras, a narrow angle tomographic approach as described in this paper could now emerge to provide a 3-D image of the flow field directly.

The paper has shown to potential for a new type of optical diagnostic, drawn on the experience and development of several previous systems, which has been created specifically for application to combustion flows. This new diagnostic has been designed as part of a Data Fusion programme [44], which merges several types of diagnostic data in order that a single goal, in this case the spatial measurement of heat release, can be made. It is hoped that from such a device the same level of efficiency gains that have been seen in the aerodynamics of turbomachinery can now be achieved in the combustion process.

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