Developments in Flow Tracing Using Miniature Lasers

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1. Abstract

At the 10th Symposium it was shown that the well established tracer gas technique can be replaced by a fast response, non-intrusive method in which the tracer gas is replaced by smoke and its local concentration is determined from the intensity of scattered laser light. Further developments are described demonstrating the extension of the technique from simple test cases to flows that are more representative of turbomachines. Particular emphasis is placed on improved equipment and experimental configurations.

2. Introduction

As three dimensional computational flow predictions become more highly developed and their range of applications is extended, reliable experimental data continue to be sought in order to evaluate these developments. The flows that may be investigated computationally now resemble more closely the real, complex flows that are found in turbomachines and in particular details such as coolant injection and tip clearance flows are being considered. Reliable data on such flows remain sparse, particularly in the field of coolant ejection, partly as a result of the difficulties of accurately tracking the flow and obtaining quantitative experimental data. Flow tracking techniques have in general fallen into one of two categories, one qualitative and the other quantitative. The most widely adopted approach has been the use of smoke flow visualisation which provides a visual but only qualitative description of the flow. Although smoke flow visualisation has been successfully used in transonic and supersonic flows (e.g. [1] , [2]) its use in high speed flows has proved to be limited due to the generally low local smoke densities and consequently poor clarity. The technique is generally associated with low speed wind tunnel studies. A more widely adopted technique in high speed flows is surface oil flow visualisation. Although this may prove invaluable as an aid to the interpretation of other measurements (e.g. [3], [4]) its value as applied to the interpretation of the bulk flow is often overrated. Quantitative information is more usefully obtained using methods such as the tracer gas technique [5] - [7]. Typically a separate gas species is injected into the airstream at a particular point and its distribution downstream after mixing is determined by sampling the gas mixture over an appropriate area or volume. The method has proved to be particularly successful in the investigation of mixing in large scale, rotating albeit low speed rigs [7]. However the method suffers from severe limitations which have a major influence upon the range of useful applications. Of these the greatest is the very slow response of the system. The time required to sample, analyse the sample and purge the analyser in preparation for the next reading limits any study to time averaged measurements which in practice can be made only at stationary points in the fixed frame of reference. Dominy [8] has described a system that combines the adaptability of smoke flow visualisation with the quantitative benefits of the tracer gas method whilst overcoming many of the major limitations of each of those methods. This is the Smoke and Scattered Light 'SSL' approach in which the tracer gas is replaced by smoke and the gas sampling system is replaced by a fast response optical system which determines the local smoke density from the intensity of scattered laser light.

3. Flow Tracking by Scattered Light Measurement

In its simplest form the SSL technique requires just four components; a smoke source, a light source, focusing optics and a photo-detector (figure 1). When a known concentration of smoke is injected into the flow the relative smoke density at any downstream point in three-dimensional space may be found by illuminating the smoke at that point and measuring the intensity of the scattered light. As a first approximation the scattered light may be considered to be directly proportional to the local smoke number density. By repeating the measurements at a number of points in two or three dimensions the dispersion of the fluid from the injection point to the measurement zone may be determined with great accuracy. Unlike conventional smoke visualisation the method not only provides quantitative data but may also be used at high speed since even the simplest detection systems are capable of resolving smoke densities much lower than those that may be observed visually.

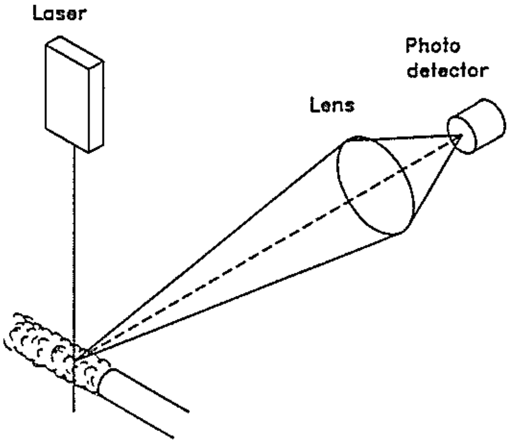

Figure 1 : Layout of Simple SSL System

3.1 The smoke source

In high speed flows smoke flow visualisation has been most widely adopted for the study of the deflection of flows through shock systems in external flows. However smoke has also been used successfully to study shock systems in transonic cascades [9]. For such applications the smoke particles must be small enough to faithfully follow the true flow path yet be large enough to scatter sufficient light to be observed, recorded or photographed. To meet these two requirements the smoke particles should lie in the range $0.15\mu m < \text{diameter} < 1.00\mu m$. The most commonly used 'smoke' sources are oil based in which the particles actually consist of condensation droplets. Water based smoke fluids have also become widely used in recent years.

In terms of the SSL technique the most important features of any smoke generator are firstly that the smoke is produced at a steady rate and secondly that it is produced in such a way that it may be injected into the flow with minimum disturbance of the mainstream flow. Since few if any smoke generators produce a sufficiently steady output to meet these conditions directly the requirements suggests a need for remote smoke generation with some form of plenum between the smoke generator and the injector to ensure uniform smoke density.

3.2 The Light Source

In principle the SSL technique may be successfully employed using any reasonable light source, white or monochromatic and the light itself may be projected into the flow either as a beam or as a sheet. The choice of white light or monochromatic light will be guided mostly by the ambient lighting conditions. If the experiment can be conducted in total darkness, then white light is perfectly acceptable. However in most laboratories it is both impractical and undesirable to operate in darkness so the monochromatic source becomes an attractive and arguably essential choice since by the use of optical filtering the light intensity incident upon the photo-detector may effectively be made independent of the ambient light level.

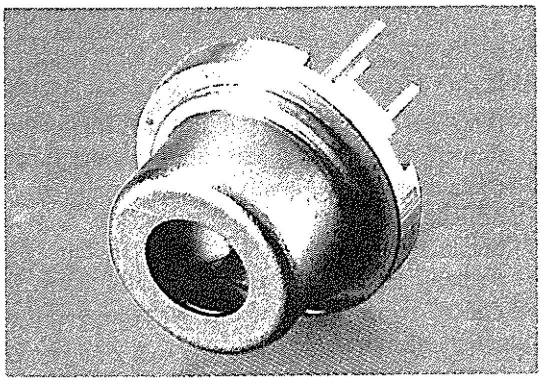

Figure 2 : Typical Laser Diode (9mm Diameter)

The rapid development in recent years of the laser diode has resulted in the ideal, low cost, miniature monochromatic source for this application. The diode itself is usually packaged in a standard transistor can (figure 2) weighing less than 1g and capable of emitting laser light of >5mW in the red or infra-red range. More conveniently such devices are readily available packaged with their associated control circuitry and collimating optics requiring just a low power D.C. supply (figure 3). The small size, weight and power consumption of these devices provides considerable potential for their use in compact spaces and on rotating components.

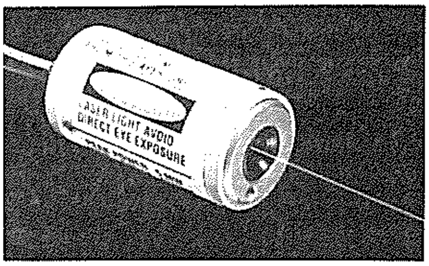

Figure 3 : Laser Diode Assembly with Internal Optics and Circuitry

3.3 The Photo-detector

Unlike the other laser techniques that have been widely adopted for measurements in fluid flows the high number density of smoke particles that are present during conventional smoke flow visualisation studies result in relatively high scattered light intensities when illuminated even in highly dispersed, high speed flows. Indeed, in most flows the scattered light is clearly visible to the naked eye. As a consequence there is no requirement for the highly sensitive photomultiplier based detection systems that are necessary for Laser anemometry. Instead, low cost photo diodes provide the foundation of an adequate detection system. For simplicity the use of readily available photo diodes with internal amplification is recommended since these provide a high level voltage output that is proportional to the incident light intensity without any additional circuitry. Such detectors may typically operate with a frequency response of about 70kHz (-3dB), this being the limiting response of the inbuilt circuitry rather than that of the diode itself. Using simpler devices frequency responses in excess of 100MHz are more typical.

3.4 The Focusing Optics

The sophistication of the optical system that is used to focus the image of a specific element of the illuminated flow field onto the receiving photo diode depends largely upon the available space for such a system. Where space is readily available as is often the case, for example, downstream from a linear cascade then the optics need consist of no more than a single element lens. The selection of such a lens depends upon the scale of the system to define the optical path lengths and hence the required focal length of the lens and also upon the geometry of the test rig which may dictate the largest diameter lens that may reasonably be adopted. The resolution of the system may be enhanced by the use of a slit or pinhole at the focal point of the system although this will inevitably reduce the received light intensity and in some situations it may prove necessary to compromise between the resolution of the system and the 'f' number in order to achieve acceptable light levels at the detector. When space is at a premium then additional optical elements may prove to be necessary. If measurements are to be made with significant background light levels it is advisable to place a narrow band optical filter, centred on the laser light frequency, between the lens or lenses and the detector to minimise the influence of background light. Generally a filter with a 10nm bandwidth is sufficient to eliminate ambient light effects even under the brightest laboratory conditions.

4. System Development

The experimental results that were presented during the early stages of the development of the SSL technique were limited to preliminary studies of the unsteadiness of the flow in the wake from the head of a smoke injection probe [8]. The developments described here are regarded as the next step towards the validation of the method for studies of complex, real flows such as those encountered in turbomachines.

Two flow fields have been investigated. The first was a study of vortex shedding behind an infinite (2-Dimensional) circular cylinder in which the measurements have centred on the detection of the shedding frequency. The circular cylinder was chosen since the results may be easily verified by simple and reliable Strouhal number correlations. Although perhaps not of direct relevance to turbomachines a proven ability to monitor such flows with accuracy and reliability has obvious relevance to trailing edge flows and flows behind struts. The second programme involved a quantitative study of the mixing of the inlet wall boundary layer as secondary flows developed through a linear cascade of turbine blades. This latter study has only recently started and the information presented here relates mostly to the experimental configuration.

4.1 System components

In both studies the chosen light source was an integral package containing a 5 mW Laser diode, collimating optics and control circuitry (figure 3). The inbuilt control circuitry provides voltage stabilisation which allows the system to be powered by a conventional 9V PP3 type battery. Further details are given in Table 1.

Type	Laser Diode : VLM2-5CF
Output	5mW (Class IIIa)
Beam Divergence	1.5 mrad
Optics	Internal, collimated
Wavelength	670 nm
Weight	13g
Dimensions (mm)	14.7 D x 28.5 L
Power Supply	5V - 10V DC

Table 1 : Laser Specification

The scattered light sensing systems adopted for the two studies were however different. For the cylinder experiment a particularly simple configuration could be adopted due to the essentially two dimensional nature of the flow. In this system the laser and the detector were positioned co-axially on either side of the wind tunnel. No additional optics were necessary. In the absence of smoke the full power of the laser beam was detected without any detectable attenuation. When smoke was present in the flow the received intensity dropped by the integral value of the scattering of the laser light over the length of the beam that passed through the smoke plume. Such a method is clearly only applicable to 2-D flows where there is no change in the nature of the flow along the length of the beam. The change in received laser power was therefore much greater than was the light intensity that would have been detected at any particular location due to scattering. It was soon found that photo diodes with internal amplification were saturated even with a 1mW laser source so a conventional photo diode was used with low gain external amplification. Details of this diode are given in Table 2.The three dimensional nature of secondary flows in turbines required the use of a scattered light detection system for the cascade experiment since it was necessary to focus upon a particular element of the beam to achieve the desired resolution. For the detection of the scattered light a photo diode was chosen with internal feedback and amplification circuitry which provided a high level, linear voltage output (Table 3).

Type	RS 305 - 462
Output Current	$0.7\ \mu V / \mu W / cm^2$
Dark Current	1.4 nA typ.
Active Area	$1.0\ mm^2$
Response Time	250 ns typ.
Amplification	External

Table 2 : Type 1 Photo diode Specification

Type	IPL 10530D
Output	$27\ m V / \mu W / cm^2$
Active Area	$1.75\ mm^2$
Supply Voltage	4V- 36VDC (or bipolar)
Response	> 65 kHz (-3dB)
Amplification	Internal

Table 3 : Type 2 Photo diode Specification

Since space was not at a premium in this study the scattered light was focused onto the detector using a single bi-convex lens of 38mm diameter and 50mm focal length. Measurements were made with and without a narrow bandpass optical filter.

For the cylinder experiment the smoke was created by an NPL type smoke probe provided by Nutem Ltd. of the kind widely used in wind tunnel studies in which an oil is vaporised at the probe tip to provide a smoke plume as it is cooled by the passing airflow. As shown by Dominy [8] the flow from such a probe is far from steady and whilst adequate for flow visualisation it is not adequate for quantitative, unsteady measurements. However with careful use this generator was considered sufficient for preliminary studies to develop the technique whilst an improved smoke source was investigated.

Smoke Generator	Concept Spirit 900
Maximum Output ...	$1.6\ m^3 / s$
..... at Density	1.5 m visibility
Heater Power	2.2 kW
Smoke Type	Water Base, Glycerine
Droplet Diameter -	
mass median	$0.2 \mu m$
count median	$0.15 \mu m$
group σ	1.37

Table 4 : Smoke Generator Specification

For the cascade study this generator was considered to be totally inadequate for numerous reasons, not least the unsteadiness, the low rate of smoke generation and the rather unpleasant nature of the smoke in the working environment! Instead a high capacity smoke generator using a safe, water based fluid was adopted (Table 4). Smoke from the generator was drawn into a plenum by a small fan before being introduced into the inlet boundary layer over two pitches at an axial location approximately one axial chord upstream of the blade leading edges. The fan and plenum combination ensured that the smoke that was fed to the boundary layer was of uniform density whilst the fan also allowed the plenum pressure to be matched to the flow pressure to minimise any influence on the nature of the wall boundary layer. The plenum also permitted cooling (or heating) of the smoke if required.

5. Experimental Results

5.1 The Two-Dimensional Cylinder

The 50mm diameter cylinder was tested over a range of Reynolds numbers from 1.5×10^4 to 1.4×10^5. With the laser axis set 0.95 cylinder radii above the cylinder axis and 2.2 radii downstream from the cylinder axis (figure 4) measurements were made of the detected beam intensity at a sampling frequency of 20kHz. The results from tests at the highest Reynolds number (1.4×10^5) are shown in figure 5 and the shedding frequency of the vortices is clearly displayed. The data are presented in terms of the reduction in recorded light intensity due to scattering as a proportion of the received intensity with no smoke present. The recorded shedding cycle frequency is 178Hz compared to a predicted frequency of 158 Hz based on the correlation for Strouhal Number :-

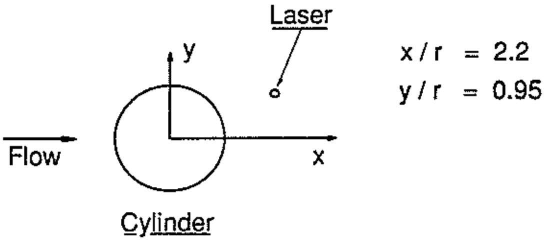

Figure 4 : Cylinder Experiment - Laser Axis Location

$$f d / u = 0.198 (1 - 19.7 / Re)$$

where f is the shedding frequency, d is the cylinder diameter and u is the free stream velocity. The discrepancy is due to the increased local flow velocity around the cylinder arising from tunnel blockage. Between the peaks there is some evidence of secondary peaks which correspond to the presence of smoke associated with the alternate shed vortex.

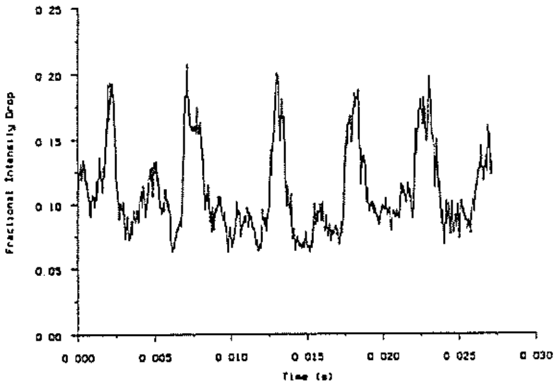

Figure 5 : Vortex Shedding From a Circular Cylinder

5.2 Cascade Secondary Flow Development Measurements.

These experiments are at an early stage and the preliminary results are not presented here. For this experiment the entire optical system was mounted on a single, rigid base plate in order to prevent rig vibration from affecting the optical alignment. The optical assembly could be traversed in either the spanwise or pitchwise directions using a pair of mutually perpendicular dovetail slides and in the flow direction by adjustment to the traverse mounting location. By moving the system as a complete assembly the problem of re-focusing the detection system for each measurement point was eliminated. Preliminary studies have shown there to be no difficulty with the detection of the local smoke concentrations under laboratory lighting conditions and quantitative concentration contours have been successfully obtained with a measure of their unsteadiness.

6 Future Developments

Although the work described here has successfully demonstrated the potential of the SSL technique in representative flows there is a great deal of detail development that is required to enhance the accuracy of quantitative measurements. One of the more important areas that must be addressed is the attenuation of the beam as it passes through the smoke field. Corrections will undoubtedly be required for such effects and an investigation of these effects is planned to determine the linearity or otherwise of the required corrections. It is also planned to investigate the technique in transonic and supersonic flows where achievable smoke densities are likely to be much reduced. This is not believed to be a major problem since the method has proved to be sensitive to similarly low smoke densities in low speed flows. Although higher smoke densities aid visual observation and hence are of great benefit when developing the system they are not essential to the success of the technique. That depends more upon the performance of the detection system to resolve small changes of intensity which although aided by increased number density may be equally improved by the use of more powerful lasers, more sensitive detection or improved optics, all of which are readily available. Further enhancements may be possible by the adoption of the latest generation of high power laser diodes (> 40mW) using line optics to create a light sheet. The experience gained with the SSL technique to date suggest that the method could have wide application in studies of film cooling, mixing, boundary layer development, separation detection and the tracking of wakes and reversed flows. Miniaturisation is also a clearly defined aim for future work enabling measurements to be made in confined spaces and potentially in the rotating frame.

7 Conclusions

The SSL technique has been successfully extended from the simplest test case to others that are more representative of turbomachinery flows. The method has now been developed to a point where it can be applied to studies of flows in cold turbomachinery rigs with reasonable confidence.

8 References

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