Fibre Optic Delivery of High Peak Power Q-Switched Laser Pulses for Flow Measurement.

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Abstract

High peak power frequency-doubled Nd:YAG laser pulses have been delivered using a bundle of optical fibres for the purpose of particle image velocimetry (PIV) of high speed flows inside automotive internal combustion engines. Data loss due to fibre speckle has been minimised by ensuring that the individual fibres in the bundle differ in length by more than the coherence length of the laser being used. This means that although the speckle patterns from each fibre will overlap, they will not interfere. Furthermore, we have shown by modelling that it is the modulation depth in the speckle (contrast between light and dark regions) that is the limiting factor rather than the size of the speckle regions involved. The issue of damage to the fibres has been addressed by the design and manufacture of a diffractive optical element to condition the laser beam and prevent the fundamental problem of self-focussing. Using this method, delivery of pulse energies in excess of 25 mJ is possible. Fibre optic bundles and associated light-sheet forming optical arrangements were designed and constructed for a series of in-cylinder PIV measurements in an internal combustion engine, including flows inside the cylinder head, where conventional free-space beam delivery could not be used. Results from these experimental trials are presented, and comparisons made with measurements generated using conventionally-delivered laser beams.

1 Introduction

Particle image velocimetry (PIV) is a well-established technique for producing full field velocity measurements in fluid flows. One of its major limitations, however, is in its requirement for good optical access to the measurement volume. Fibre optics offer a potential solution.

Fibre optic delivery offers distinct advantages over conventional bulk-optic-delivered light sheets. Firstly, access to hard-to-reach regions is offered. Secondly, the laser system can be isolated from vibration in the test-rig; the optics producing the light sheet can be securely mounted to a vibrating workpiece, along with a camera to capture images for PIV, whilst the (relatively large) laser that produces the light sheet can be left separate. Thirdly, alignment is greatly simplified because the fibre output optics can be made as a single, portable unit; there are no mirrors or lenses to align to produce a light sheet in a particular plane in space, instead there is simply a fibre optic cable running from the laser to the working region. Lastly, there is a safety aspect. Unlike conventional bulk-optic beam delivery, the only laser beam that exists in unguarded free space is the light sheet itself. Everything else can be safely and easily contained within permanent guarding.

PIV for analysis of high speed flows requires laser pulses with durations of approximately 10 ns and energies of between 10 mJ and 100 mJ, dependent on the area and thickness of the required light sheet and the diameter and type of particles that are being used to seed the flow that is being measured. The fibre delivery system must be capable of providing the right combination of peak power delivery and beam quality (focusability) to produce the sheet. Beam quality is usually defined using the M^2 parameter, where

$$M^2 = \frac{\alpha_0 w_0}{\left(\lambda / \pi\right)} \qquad \textit{Equation 1}$$

where α_0 is the focus cone half-angle, w_0 is the radius of the focussed spot, and λ is the laser wavelength. An M^2 value of 1 corresponds to a 'perfect' laser beam (i.e. with fundamental Gaussian intensity profile). In reality, all beams have $M^2 > 1$, ranging from $M^2 \sim 1.1$ for very high beam quality lasers to M^2 values of a few hundred for low beam quality but high power welding lasers.

It is clear from equation 1 that a long (small α_0), thin (small w_0) light sheet requires a high beam quality (low M^2 value). For example, for the relatively small light sheets required in the internal combustion engine application of interest here — typically 60 mm × 60 mm × 1-2 mm — a beam with an M^2 value of ~100 or less is required. This may be achieved with a 200 μm diameter fibre, but unfortunately the pulse energy that can be delivered is too low. A bundle of 19 fibres is therefore used to improve the compromise between delivered pulse energy and beam quality in the light sheet. The fibres at the input end of the bundle are formed into a circular array, whilst at the output end the fibres are aligned in a linear array—see Figure 1. The beam quality in the plane in which focusing is required to produce the sheet is hence the same as for a single 200 μm fibre. The beam quality in the orthogonal direction is correspondingly reduced; however this is unimportant as the beam is not focused in this direction. Using this design, we have successfully delivered many thousands of 25 mJ, 8 ns pulses.

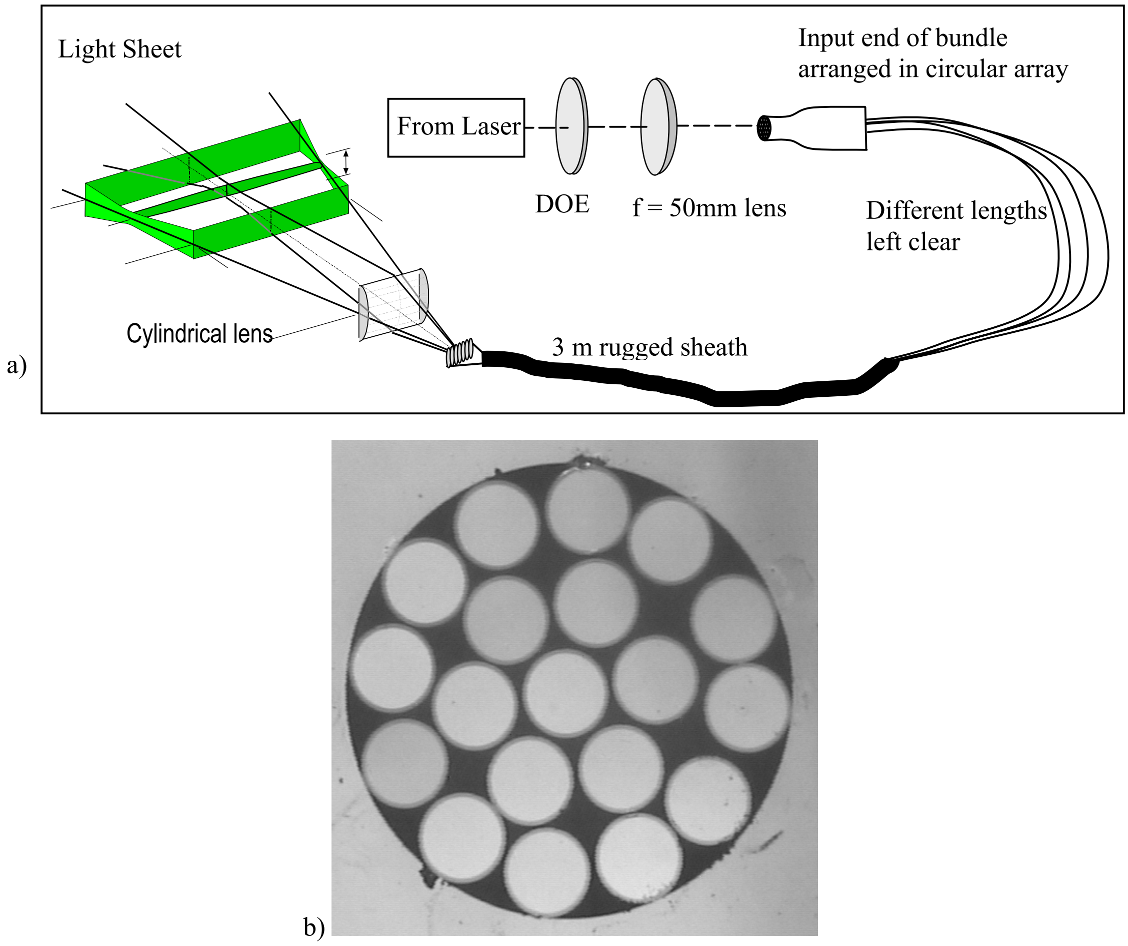


Figure 1: (a) Schematic illustrating the design of the bundle; circular at the input and linear at the output. A micrograph (b) shows the circular input array.

2 Fibre Damage

If a short pulse of laser light is coupled into an optical fibre damage can occur by two quite different mechanisms. The first mechanism is thermo-mechanical damage to the end face. Small imperfections in the fibre face scatter the laser pulse, causing absorption and thus damage. This damage mechanism is prevented by careful preparation and cleaning of the end-face.

The second mechanism is driven by the non-linear optical effect known as self-focussing. The refractive index of the medium through which the laser pulse is propagating (in this case, glass) changes relative to the intensity of the light incident on it. The gaussian-like transverse intensity profile of the beam produces what is effectively a graded refractive index lens. If the intensity is high enough, the magnitude of this refractive index change will overcome beam diffraction and focus the beam until damage occurs, approximately 1 mm behind the front face of the fibre. This can occur at relatively low pulse energies — e.g. 5 mJ for a 400 μm diameter fibre (Anderson, D.J. et al. (1995)). If the number of modes in the fibre which are populated is increased, then each individual mode contains less energy and therefore self-focussing is less likely to occur (Hand, D.P. et al. (1999)); however in order to achieve this, the quality of the beam needs to be matched to that of the fibre. Matching occurs when the focal spot radius (beam waist) is equal to the fibre core radius *and* its focusing convergence angle is equal to the acceptance angle of the fibre.

However, the laser typically used for PIV measurements (frequency-doubled Nd:YAG) normally has a high beam quality, due to the requirement for efficient frequency-doubling. We have therefore designed and manufactured a diffractive-optical-element (DOE), which controllably degrades the beam quality and, together with a suitable lens, produces a 'top hat' intensity profile with a diameter that matches that of the input end of the bundle. A DOE is essentially a computer-generated hologram and has surface relief in the form of a periodic pattern to diffract light (Miller et al (1993)). The DOE manufactured in this case is a single level design, and therefore only 63% of the pulse energy incident on it is directed into the first order, with the remaining energy going into higher, off-axis orders. With multi-level designs this efficiency can be increased to almost 100% (Goodman J.W. and Silvestri A.M. (1970) and Taghizadeh *et.al.* (1997)).

The image of the beam produced by the DOE in combination with a 50 mm focal length lens is shown in Figure 2. It is clear that this although most of the optical fluence is contained within a 'top hat' profile as required, there is a high intensity peak in the centre. This is the undiffracted (zeroth order) beam, and is present due to manufacturing defects and the tight tolerances involved. When this DOE was used to couple light into the bundle, the central peak caused the central fibre in the bundle to damage. However, it was still possible to transmit 20 mJ through the bundle without damage to the other fibres.

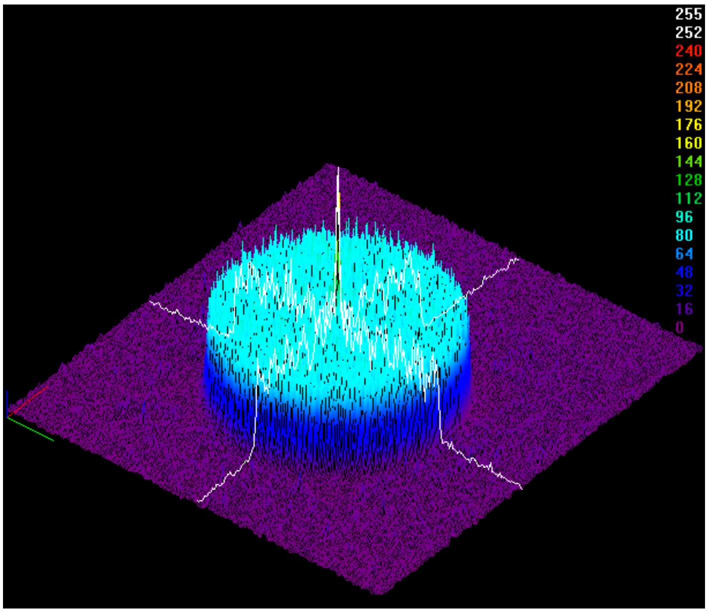
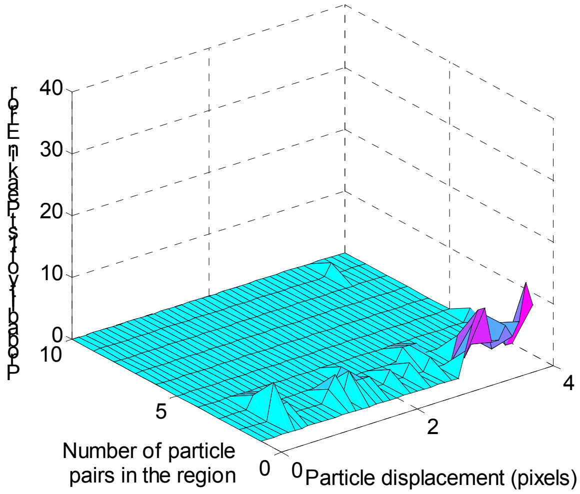


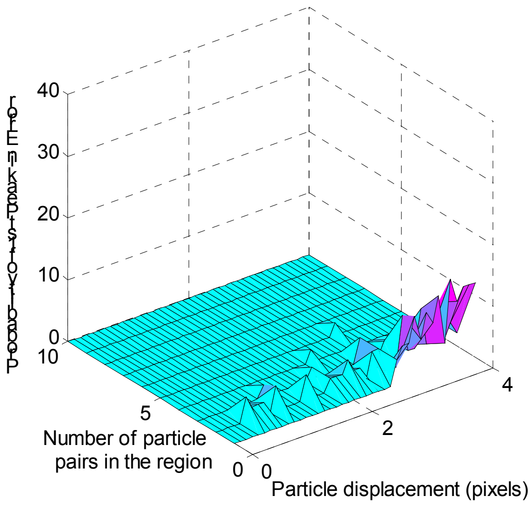
Figure 2 : False colour image showing the intensity profile of the DOE. The central, zero-order peak can be clearly seen.

3 Speckle

The use of multi-mode fibres introduces the issue of fibre speckle. Speckle is the superposition of the many guided modes that exist within the core of a multi-mode optical fibre, and it produces a mottled output pattern from the fibre. This variation in intensity at the output may affect the quality of data that are captured from the resulting light sheet. Brightly illuminated particles in one image of the PIV pair may not appear in the second image due to a lower intensity in the region through which they are moving. A model was developed to simulate speckled light sheets and determine their effect on PIV measurements. This model generates pairs of PIV images with known particle displacements between them, for a given speckled light sheet. Real and simulated speckle fields as well as evenly lit fields were used in the model to illuminate the particles in the images. The simulated speckle fields were of a chequerboard pattern where the size and contrast of the regions could be controlled. The images are then processed with a standard cross-correlation algorithm (Keane, R.D. and Adrian, R.J.,(1993)) and the result is compared with the known particle displacement. This allows the effect of the speckle on data quality to be quantified. As a measure of performance, we chose to look at the probability that the strongest peak in the correlation plane is in error. Examples are shown in Figure 3, where the probability of the first peak being in error is plotted as a function of particle displacement and the number of particle pairs in the region for three different speckle patterns. It has been found that reducing the contrast between light and dark regions, analogous to lowering the modulation depth in the speckle, has the effect of reducing the probability that the first peak is in error. Similarly, speckle regions larger than the average shift of particles in the image produce a lower probability of error.



a)



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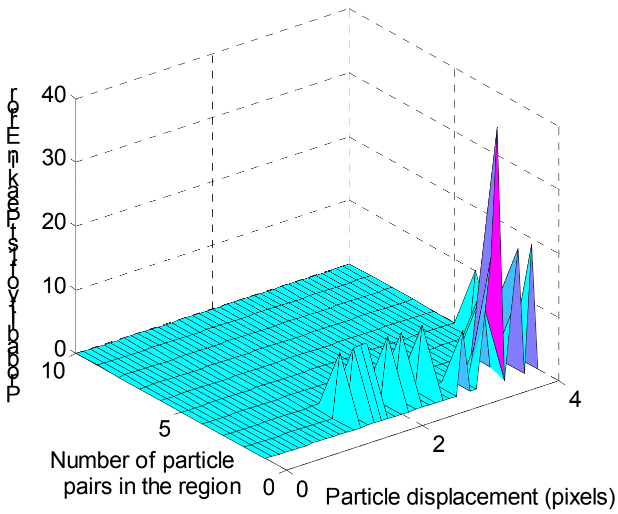


c)

Figure 3: Probability (%) of first peak being in error for an image illuminated (a) evenly; (b) a speckle pattern from 19 fibres and (c) the speckle pattern from 4 fibres. The Probability of an error increases as the sheet becomes less evenly lit.

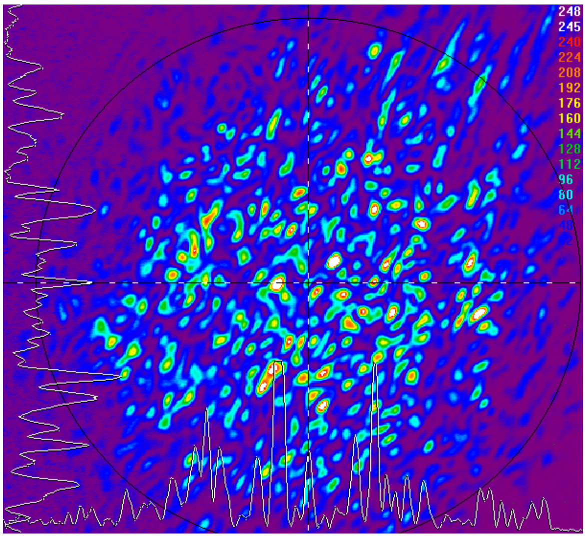


Figure 4: False colour image showing a typical speckle pattern from a single 200µm multi-mode optical fibre. The curves shown across the left-hand and bottom axes correspond to the intensity values along the cross hairs in the image.

To further test these conclusions, two types of bundles were constructed and tested. The first type consisted of fibres of the same length whilst in the second each fibre was different in length from every other by at least 25 mm. The coherence length of the laser used for this experiment was measured to be 16 mm in fused silica. In each case, the number of fibres in the bundle was incremented from one to nineteen and a near field speckle pattern was recorded. Qualitative comparison between Figure 4 and Figure 5 allows us to deduce that the speckle field is more even .To quantify the evenness, a sample of 10 rows of pixels was taken from each image. Each slice was normalised to remove the intensity fall-off at the edges, since we are interested only in the *modulation* of the speckle. This normalised data was analysed by counting the number of pixels that have an intensity greater than a particular percentage of the maximum value. The number is plotted as a function of this percentage in Figure 6, (a) for the bundle where all the fibres are the same length ±5 mm; and (b) for the bundle where all fibres are at least 25 mm different in length. Figure 6(c), meanwhile, shows the data from (a) subtracted from (b). A perfectly evenly lit row (i.e. the optimal light sheet) would appear as a step with the edge at 100% on the x-axis. It is clear from Figure 6(a) and Figure 6(b) that increasing the number of fibres results in a more uniform light sheet Figure 6(c) demonstrates that a bundle with different length fibres produces a more even light sheet than one where each fibre is the same length.

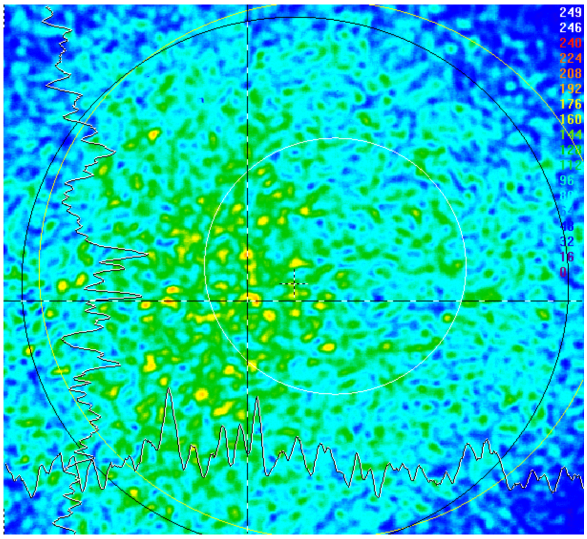
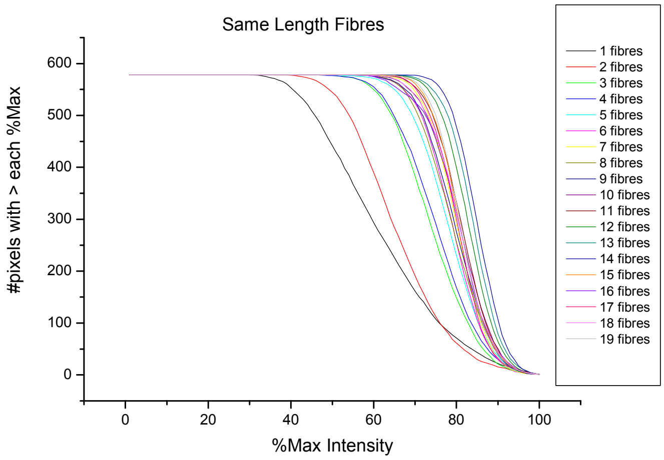
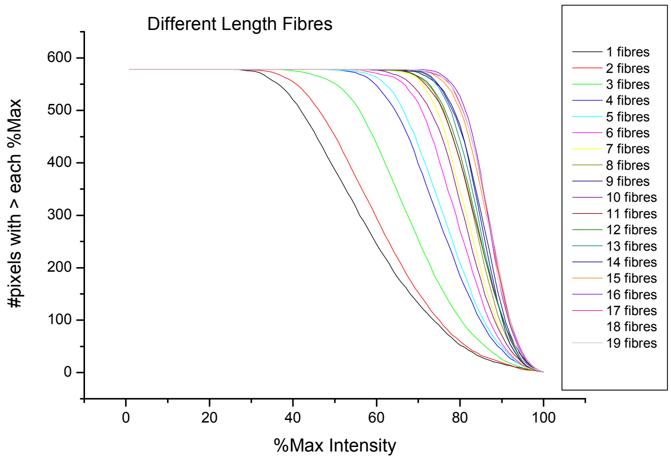


Figure 5 : False colour image of the near field speckle pattern from a linear array of 19, different length, 200µm fibres.



a)



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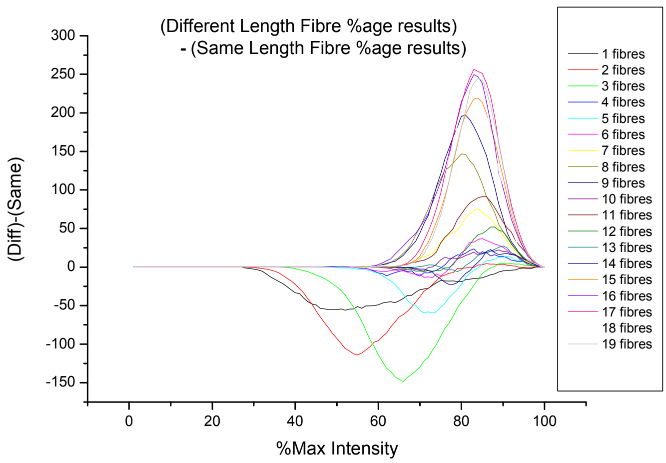

c)

Figure 6:Graphs showing how many pixels from a sample of 10 rows in a normalised speckle pattern have an intensity greater than a particular percentage of the maximum value in that row. A perfectly evenly lit row would appear as a step with an edge at 100% on the x-axis. (a) Shows a bundle where all the fibres are the same length ±5 mm; (b) Shows a bundle where all fibres are at least 25 mm different in length (coherence length if laser in glass is 16 mm); and (c) shows the data from (a) subtracted from (b).

4 In-Cylinder Measurements

PIV measurements have become an important tool in the development of new types of internal combustion engines, but the confined spaces in which the measurements must be made offer a challenge that in some cases can only be met by fibre optics (Beeck M-A. and Hentschel, W. (2000) and Reeves, M. et al. (1994)). We describe a series of in-cylinder measurements recorded in collaboration with an automotive manufacturer using a special 'optical engine' with a glass cylinder section and polycarbonate piston. This optical engine allows many PIV measurements to be made using standard optical delivery systems; of particular interest here, however, was a series of measurements within the cylinder head to which there is no direct optical access. To enable these measurements, a special fibre-optic probe was developed which could be inserted into an available port in the cylinder head, which had a minimum diameter of 8 mm. This probe housed the linear array output end of the fibre bundle, together with beam conditioning optics to generate the light sheet. In addition, the fibre bundle was used for PIV measurements by illumination through the glass barrel, in order that a back-to-back comparison could be made with the conventional optics delivery system. For all these measurements, the optical engine is driven by an electric motor to achieve a modest speed of approximately 1000 rpm, producing a maximum pressure of 10 bar (since the engine is not fired).

4.1 Bundle construction

The fibre optic bundle used for these experiments was similar to that described earlier, consisting of nineteen, 200 µm diameter fibres, arranged in a hexagonal close packed (circular) formation at the input end and a linear array at the output. Each fibre is different in length by at least 100 mm and the total length of the bundle is approximately 4 m. Since the input end of the bundle is subjected to very high pulse energies the fibres cannot be held by glue at this point; instead a tapered glass capillary tube is used. The output end does not have an optical field incident on it, so glue can be used here without causing damage — the fibres are mounted in a fused silica v-groove array with epoxy resin and the ends subsequently polished flat. The beam that is launched into the bundle is first conditioned by the DOE, described in section 2, which with a suitable lens (f = 50mm) produces a top-hat distribution with a diameter of 1.1 mm, matching that of the circular array of fibres at the bundle input end.

4.2 Fibre optic probe

In order to measure flow inside the cylinder-head of the optical engine, the fibre bundle was essential as there is no direct optical access; the only access being via a 8mm diameter port in the cylinder head close to the valves, and approximately 3 mm above the cylinder head face. As a further complication, the port is at an angle of 35˚ to the required measurement plane. Given these constraints, a probe was designed and built. A schematic diagram is shown in Figure 7. A spherical lens of focal length 50 mm is used to collimate the beam emerging from the bundle, followed by a pair of crossed cylindrical lenses with different focal lengths (100 mm and 25 mm) to form the light sheet. Two mirrors were also required; (a) to re-direct the beam just outside the port due the limited clearance available and (b) to create the light sheet at the required 35° angle to the port. A sapphire window placed before this last mirror was used to provide an air-tight seal, up to a pressure of 10 bar, the maximum experienced in the (non-fired) engine. The final mirror (made of polished stainless steel) quickly becomes contaminated with the oil droplets used to seed the flow, and so this was designed to be easily removable to allow cleaning. A photograph of the probe is shown in Figure 8.

The light sheet thickness is plotted as a function of distance from the probe tip in Figure 9. This shows that over the region of interest (0 - 30 mm from the probe tip), the thickness was < 2 mm, as required for the application.

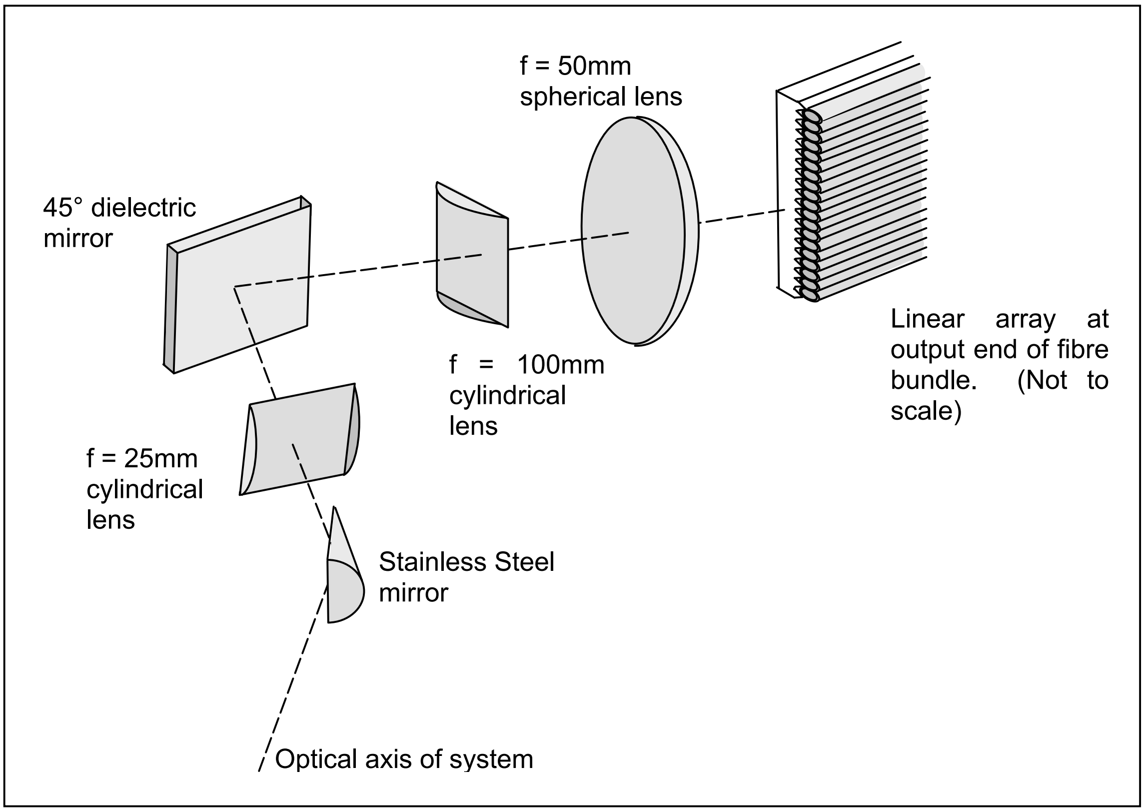

Figure 7 : Schematic diagram of the optical setup within the probe.

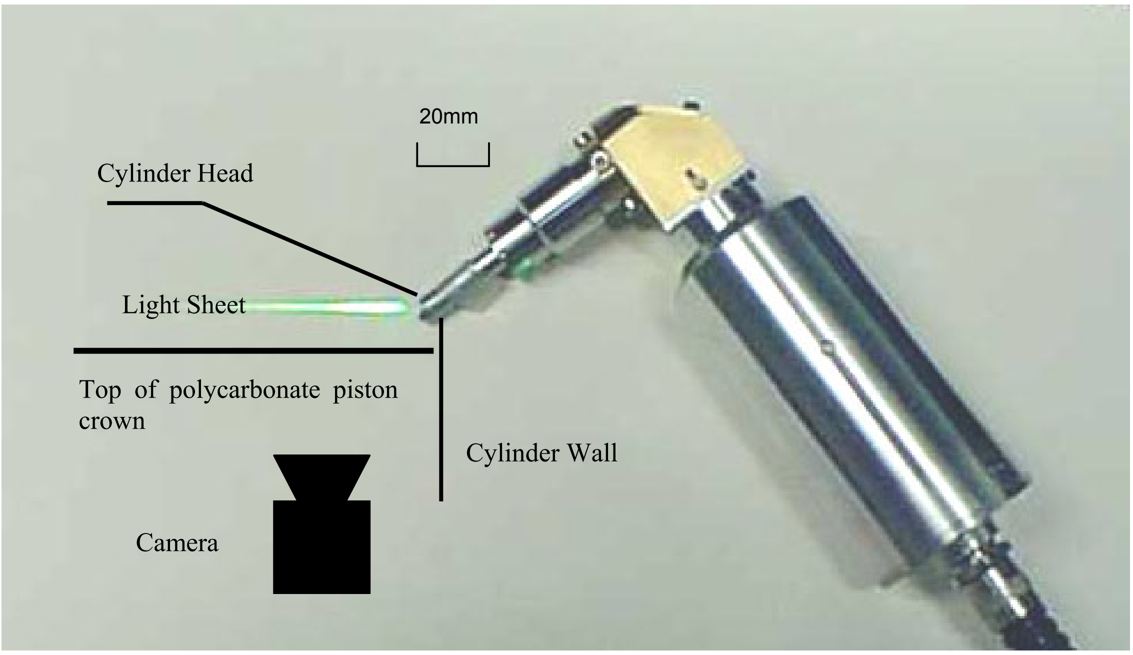

Figure 8 : Photograph showing the probe and how it is oriented in the engine.

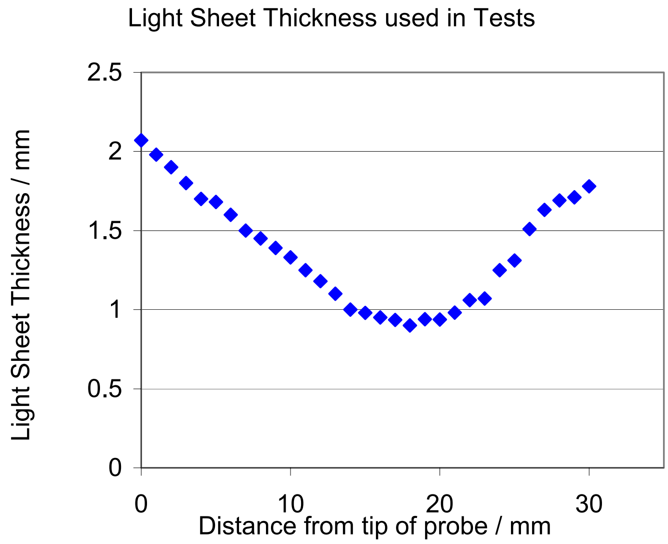

Figure 9 : Graph showing thickness of light sheet used in the tests inside the internal combustion engine.

4.3 Results

4.3.1 Back-to-back comparison; fibre bundle vs. conventional optics

An area of 33 × 40 mm along the bore-centreline was illuminated by light sheets of nominal thickness 1 mm through the glass wall of the barrel, using both fibre bundle and conventional optics delivery. The pulse energy delivered to the measurement volume was 20 mJ in each case, ensuring that the light sheets were as similar as possible in order that a valid comparison between the data quality could be made. Performance of the different beam delivery systems was assessed by measuring the percentage of the optimised PIV data that belong to each of the five strongest peaks in the correlation plane. For an ideal system, 100% of the best-fit vectors would belong to the first correlation peak. In practice this value is never achieved, since this measurement is sensitive to the velocity, size and out of plane flow of the particles and the timing and intensity of the laser pulses. Thus, the more best-fit vectors that exist in higher order peaks, the poorer the data quality in the PIV images. From Figure 8, it can be seen that the data collected using both fibre and bulk optic delivered light sheets are of very similar quality.

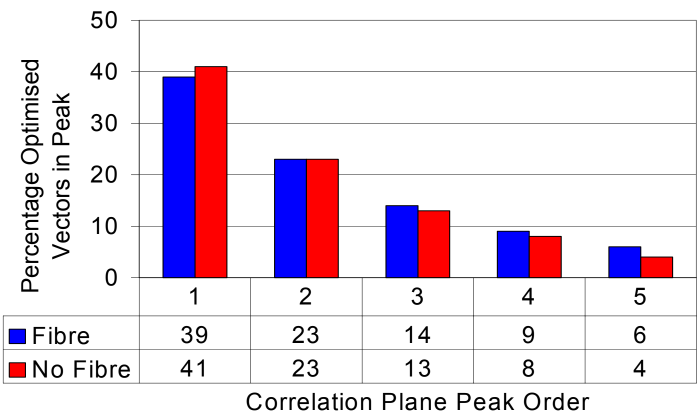

Figure 10: Graph showing the percentage of best-fit vectors that belong to each of the five highest peaks in the correlation plane. Results are given for both fibre and bulk-optic delivered light

4.3.2 Measurements inside the cylinder head

The optical probe was used to create a light sheet 2 mm above and parallel to the cylinder head face. Using a pulsed Nd:YAG as before, pulses of energy 19.6 mJ were delivered through the bundle. The cylinder was accessed through a narrow port, causing a great deal of vignetting, even with carefully designed optics, reducing the pulse energy that could be delivered to the fluid flow to approximately 1 mJ. An area of 26 × 15 mm was illuminated by the light sheet, which was approximately 1 mm thick across the region. A series of runs were performed, each with three different inlet manifold configurations, at 30°BTDC and TDC, capturing 75 pairs of images in each case. Images of the area were taken from below using a special PIV camera looking through the piston crown, which was manufactured from polycarbonate. The results were analysed as before, using PIV analysis software and ensemble averages were calculated. A typical flow vector map obtained is shown in Figure 11. The results obtained mostly agree with those predicted by standard Computational Fluid Dynamics (CFD) modelling.

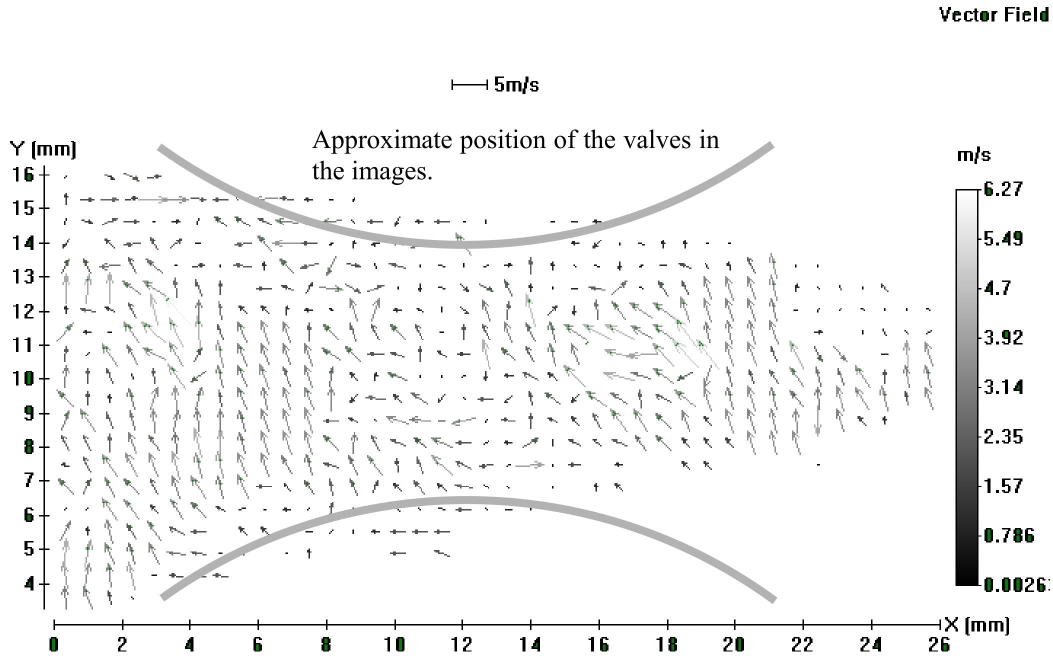

Figure 11 : Sample image from PIV analysis software. The light sheet can be seen to diverge from where it emerges from the port on the right-hand side.

5 Summary

A bundle of optical fibres has been successfully used to deliver high-peak-power laser pulses for the purpose of particle image velocimetry in an internal combustion engine. Optical damage to the fibres was avoided by the use of a diffractive optical element to condition the laser beam before coupling into the fibres, and by careful preparation of the bundle end face. We demonstrated that a fibre bundle-delivered light sheet can be used to produce images of a similar quality those produced with a bulk-optic delivered light sheet, and this bundle was subsequently used to make PIV measurements inside the cylinder head of an internal-combustion engine without modifying the geometry to allow optical access. In conclusion, we have demonstrated that fibre optics allow access to regions where PIV would not otherwise be possible, and can generate data of equal quality to that collected by conventionally delivered light sheets.

6 References

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