Time Resolved Digital PIV Measurements of Flow Field Cyclic Variation in an Optical IC Engine

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Abstract. Time resolved digital particle image velocimetry (DPIV) experimental data is presented for the in-cylinder flow field development of a motored four stroke spark ignition (SI) optical internal combustion (IC) engine. A high speed DPIV system was employed to quantify the velocity field development during the intake and compression stroke at an engine speed of 1500 rpm. The results map the spatial and temporal development of the in-cylinder flow field structure allowing comparison between traditional ensemble average and cycle average flow field structures. Conclusions are drawn with respect to engine flow field cyclic variations.

1. Introduction

The recent application of optical based diagnostic techniques has given an improved understanding of spark ignition (SI) internal combustion (IC) engine in-cylinder phenomena [1]. However, insight into the temporal nature of the complex in-cylinder flow field is still required for future engine development needs [2]. The main challenge of today’s automotive engineers tasked with IC engine design is to improve engine fuel consumption whilst reducing pollutant emissions [3]. At this point in IC engine development it is recognised that the conditions caused by cyclic variation within the engine cylinder are limiting full potential [3].

It is well documented that the fluid motion generated within a multi valve SI IC engine cylinder during the intake and compression stroke has a fundamental affect on engine performance and emissions [2,4,5,6]. Structures generated during the intake stroke, such as tumble or swirl, maintain the kinetic energy of the fluid motion and promote air/fuel mixing until late in the compression stroke [6]. At this stage in the cycle, prior to ignition, the kinetic energy present in the flow field is dissipated as large scale structures are broken down to smaller scale turbulent structures that promote early flame growth [6]. Variations in the large scale flow field structures present during the intake stroke and small scale structures during the compression stroke, result in variation in the combustion processes by affecting the mixture preparation and flame front wrinkling. The difference in parameters, such as flow field velocity and turbulent flame front propagation speed from one cycle to the next is termed cyclic variation [2]. If the variation is excessive, it results in in-complete combustion, which is detrimental to engine performance by reducing power output and increases emissions [6].

Previous Particle Image Velocimetry (PIV) studies of in-cylinder fluid motion have primarily concentrated on the acquisition of instantaneous velocity fields, ie once per cycle. Early examples such as Reeves et al. [4], involved the measurement of in-cylinder flow field velocity at single crank angle
measurement points for varying inlet conditions and provided useful insights into in-cylinder phenomena. Recent advances in laser and camera technology have allowed the acquisition of multiple in-cylinder velocity fields during the same engine cycle. More recent work presented by Reeves et al. [2] highlighted the use of a high speed laser and camera combination for the capture of in-cylinder PIV images at 9000 frames per second. Further high speed work by Towers and Towers [7] also presented the use of a high speed PIV system for determination of a cycle average flow field. Both examples used a copper vapour laser and high speed digital camera to image a horizontal plane within an optically accessible IC engine, recording flow field velocities over a number of crank angles and engine cycles.

This study presents the application of a new high resolution high speed DPIV system for determination of cyclic variation within a motored four valve optical research engine. The synchronization of the engine with the high speed diagnostic system allowed the capture of velocity field data at 1.8 crank angle degree intervals for up to ten consecutive engine cycles. Characterisation of cyclic variation for a single engine cycle is presented based on the difference between ensemble average and cycle average flow fields.

2. Experimental

2.1. Optical IC Engine

Experimental measurements were completed on a single cylinder four stroke motored optical engine designed and built by the Advanced Powertrain Group of Jaguar Cars. The engine incorporated a fused silica liner, piston crown and pent roof window to provide full optical. A schematic of the optical engine is presented in Figure 1, highlighting key engine and optical access components. The engine was based on a production four valve cylinder head and cylinder bore and stroke geometry.

A motoring/absorbing electric drive system was utilised to operate the engine at 1500 rpm with an accuracy of ± 1 rpm. A 0.1 Crank Angle Degree (CAD) incremental optical encoder was fitted to the engine crank shaft output to provide accurate engine positional and speed measurement, together with markers for triggering the high speed data acquisition. The intake system, incorporating throttle, air bleed, flow seeding system and plenum chamber allowed accurate control of manifold pressure. For results presented in this paper the manifold pressure was set at 700 mbar, matching a standard part load test point.

2.2. Laser Diagnostics

A new high speed DPIV system was employed to provide both spatial and temporal velocity field measurements of air motion within the engine combustion chamber. The system consisted of a Newwave Pegasus Nd:YLF double pulse high speed laser, synchronised to a TSI Powerview HS3000 CMOS camera for two frame PIV capture. A schematic of the measurement system is presented in Figure 2 highlighting the introduction of the laser sheet, and subsequent imaged area. The laser output, at 527 nm with 10 mJ per pulse at 2 kHz, was formed into a vertical sheet of approximately 35 mm width by 1 mm depth and introduced into the combustion chamber through a piston window via a 45° mirror. For the work presented in this study the high speed camera was operated with a resolution of 512 pixels by 512 pixels at 10000 frames per second. A 105 mm AF Micro Nikkor lens was used to image an area of 17.5 mm × 17.5 mm within the combustion chamber.

A multi jet atomiser was used to generate olive oil tracer particles of nominal diameter 1-2 μm. Tracer particles were introduced into the intake air flow prior to entering the engine plenum chamber. The flow tracing particles utilised in conjunction with the imaging lens at an f-number of 5.6 provided an average measured image particle size of 1.5 pixels.

Image pairs were analysed using a two frame FFT cross correlation routine incorporating a Gaussian peak search algorithm within the commercial software package, Insight. For the results presented in this study 20 cycles of data were captured and analysed using a recursive grid routine with a 50 % Nyquist overlap. The initial pass size incorporated an interrogation region of 64 pixels × 64 pixels. A second pass was employed with a frame ‘a’ interrogation region size of...
32 pixels × 32 pixels, and a frame ‘b’ interrogation region size of 64 pixels × 64 pixels. The 32 pixel interrogation region employed equated to 1.16 mm by 1.16 mm spaced at 0.58 mm.

3. Results and Discussion

The application of a high speed PIV system facilitated the quantification of in-cylinder flow field temporal development over a number of engine cycles. For the data presented in this study measurements began at 140.0 CAD After Top Dead Centre (ATDC) on the intake stroke and continued to 320.0 CAD ATDC on the compression stroke. Velocity field data with a separation of 1.8 CAD over a total of 10 consecutive cycles was captured, however, for the purpose of this publication, only examples of the flow field development over the range 194.0 CAD ATDC to 201.2 CAD are presented. Figure 2 provides instantaneous velocity field data acquired on one individual cycle of the measured sample, highlighting the typical flow field structures seen within the engine combustion chamber. Figure 2(a) corresponds to 194.0 CAD ATDC as the piston is traveling towards TDC on the compression phase of the engine cycle. A bulk upward motion is apparent in the measurement plane, with a global velocity magnitude of approximately 7 ms⁻¹. Interestingly, spatial fluctuations in the velocity field can be seen throughout the measurement region with areas of high velocity magnitude reaching 10 ms⁻¹, and apparent small scale recirculation velocities of around 1 ms⁻¹. Figure 2(b) highlights a similar trend in velocity magnitude, however, development of small scale structures are apparent. Flow direction arrows added to the figure demonstrate the progression of the small scale structure within the measurement plane. In the lower section of the measurement plane, regions of high velocity magnitude can be seen to develop, moving slowly from left to right across the image window. Regions of slower flow in the upper section of the planar measurement window begin to develop as the field progresses with increased crank angle. Noticeably, the small scale recirculation prominent in the upper left hand region of the image plane, appears to reduce in size over the crank angle interval.
Figure 2. Example of instantaneous velocity field captures from 194.0 CAD ATDC to 201.2 CAD ATDC, with 1.8 CAD separation between frames. Velocities are presented in ms$^{-1}$.

Figure 3. Ensemble averaged velocity fields for 194.0 CAD ATDC to 201.2 CAD ATDC, with 1.8 CAD separation between frames.
Comparison of the instantaneous velocity fields presented over the 7.2 CAD period to those of the ensemble average, presented in Figure 3, highlight a global upward bulk motion within the image window. However, with respect to the instantaneous cases, the ensemble average velocity field shows a large reduction in velocity magnitude and as expected small scale motions, as the process of calculation removes the high frequency components of the flow. The calculated ensemble average velocity fields presented represent the same crank angle positions as those shown in Figure 2. The global velocity field at 194.0 CAD has a typical magnitude of approximately 2 m/s. Progressing through the crank angle positions highlights the development of areas where the flow velocity magnitude increase to a value of 4 m/s. The general trend of the flow field direction highlights a large scale recirculation with centre slightly offset to the cylinder central axis. This bulk motion is a representation of the tumble motion generated as intake air flows through the valve curtain area. The intake flow interacts with the cylinder wall and piston crown to form a recirculation structure depicted in the schematic image of Figure 3.

Methods for analysing cyclic variability in IC engine in-cylinder flow fields have been presented by a number of investigators based on the acquisition of temporal velocity data. For analysis of instantaneous captured flow field data the use of a standard Reynolds decomposition, involving an ensemble average calculation is common [8]. The availability of time resolved velocity data allows the further derivation of a cycle average velocity. Comparison of the difference between the two averaging techniques provides an indication of cyclic variation [7]. For the data presented in this study the ensemble average was calculated over 20 cycles.

The cycle average velocity was calculated based on the PIV measured temporal development of the flow field through an individual engine cycle at each interrogation region location. The temporal u and v components of the velocity development at each location through one cycle were transferred to the frequency domain using a one-dimensional Fast Fourier Transform (FFT). A low pass filter utilising a cut off frequency of 300 Hz was then applied to remove high frequency portions, equivalent to the small scale flow field turbulence. The frequency cut off level was based on the published range of 0 - 400 Hz for IC engine bulk motion [9], and analysis of recirculations resolved in-cylinder utilising the current diagnostic technique. The resulting temporal velocity trace provides an average velocity development specific to that particular engine cycle.

Examples of the calculation of ensemble and cycle average in-cylinder velocity have been presented by both Towers and Towers [7] and St.Hill et al [10] for the indication of cyclic variability. St.Hill et al [10] detailed the application of a Laser Doppler Anemometry (LDA) measurement system to provide the temporal point measurement of flow velocity, however the technique lacked any true spatial information. Further to this Towers and Towers [7] utilised a high speed PIV technique that allowed both spatial and temporal velocity field data acquisition. However, the resolution of the recording medium was only 128 pixels × 128 pixels, with each pixel representing 0.31 mm. This equated to a PIV interrogation region size of 5 mm × 5 mm. Ensemble averages were also calculated over a total of 15 engine cycles. The present study highlights the application of an increased resolution capture with interrogation region size of 1.16 mm × 1.16 mm, providing improved accuracy for velocity measurement, and ensemble average calculation over 20 engine cycles.

Figure 4 presents the cycle average velocity field for the instantaneous case presented previously. A similar trend to that of the ensemble average velocity field can be seen over the five crank angle positions. The cycle average represents the bulk motion of the flow in a similar manner to the ensemble average, however the cycle average field does include some smaller scale structures. This is a direct result of the FFT cut off frequency chosen. For all positions, the imaged region has a typical global velocity magnitude of 5 m/s, which appears larger than that of the ensemble average case. Interestingly a slower region within the cycle average flow field can be seen to propagate from the upper left hand section, moving out of the image window. This can be compared to the small recirculation structure seen in the instantaneous example. Thus, the cycle average provides an indication of some of the dominant small scale structures present in the instantaneous flow field, whilst retaining the global bulk motion seen in the ensemble averaged case. However, it is of note that the choice of frequency cut off filter is fundamental to the scales of fluctuations seen in the cycle average velocity field.
Figure 4. Calculated cycle mean velocity field for 194.0 CAD ATDC to 201.2 CAD ATDC, with approximately 1.8 CAD separation between frames. Velocities are presented in ms$^{-1}$.

Figure 5. Example plot of a.) Instantaneous $u$ velocity, Ensemble averaged $u$ velocity, and Cycle averaged $u$ velocity, b.) Calculated Cyclic variation, for a given (x,y) location within velocity field shown in Figure 2.
To further compare the temporal development of the in-cylinder flow field over the duration of the engine cycle Figure 5a.) presents measured instantaneous, calculated ensemble and cycle average data. The figure shows the instantaneous $u$ component velocity temporal development for an arbitrary interrogation region, within the measurement plane. Analysis of the instantaneous plots highlight the high frequency fluctuations in the velocity captured at 1.8 CAD intervals over the intake and compression phase. Throughout the 180 CAD period the magnitude of the $u$ velocity component can be seen to peak at approximately 175 CAD, and 220 CAD reaching values in the region of 6 ms$^{-1}$. A final peak can also be seen in the later stages of the cycle at approximately 290 CAD. Analysis of the ensemble average velocity component for the same interrogation region highlights a smoothing of the instantaneous case. The initial peak in velocity is represented in the ensemble average case, however the remainder of the cycle shows a distinct smoothing of the velocity development. The high frequency fluctuations also seen in the instantaneous case are not apparent in the ensemble average calculation highlighting the bulk motion of the flow field shown in figure 3. The cycle average trace follows a similar trend in the initial stage of the engine cycle to that of the ensemble case, however the cycle average velocity is more representative of the instantaneous velocity in the later stages of the engine cycle. Points of peak velocity in the instantaneous case are matched in the cycle average case at 175, 220 and 290 CAD.

Using the theory presented by both Reeves et al. [2] and Towers and Towers [7] the cyclic variation for an individual cycle, detailed in this work, was calculated to highlight regions of variation. Figure 5b.) presents the cyclic variation for the example measurement point discussed previously, calculated as magnitude of the difference between ensemble mean velocity and the cycle average velocity. The figure helps to highlight variation in the measurement field at each crank angle position over the engine cycle. Over the initial period the cyclic variation is relatively low, however after the piston has progressed passed Bottom Dead Centre (BDC), 180 CAD, the variation between cycle and ensemble average velocity increases. The cyclic variation reduces towards the end of the measurement period, from 280 CAD onwards, suggesting less flow field variation at this point as the time of mixture ignition is approached at 313.5 CAD.

Figure 6. Calculated in-cylinder cyclic variation for frames 194.0 CAD ATDC to 201.2 CAD ATDC, presented in Figure 2
Cyclic variation analysis of both $u$ and $v$ components for the whole measurement window is presented in Figure 6 for the five crank angle positions discussed. Over the period 194.0 CAD to 201.2 CAD it is clear that the cyclic variation for this particular engine cycle measurement plane reduces as the regions of higher variation decline. At 194.0 CAD the lower right hand section of the image window shows a region of high variation. This section of the flow field, when compared to the instantaneous case, highlights the location of a high velocity magnitude region. The development of this region of larger variation mirrors the reduction in higher velocity in the lower section of the instantaneous cases. Regions of less variability are matched to the slower areas of the instantaneous measurements. The results presented in this paper represent a small section of the engine cycle. Analysis of the flow field for all crank angle positions help highlight the breakdown of large scale bulk motion to small scale turbulent structures. With the magnitude in variation of bulk motions early in the cycle being larger than the variation in small scale structures generated towards the end of the compression process.

4. Conclusion

This paper has described the application of high speed digital particle image velocimetry to the measurement of IC engine in-cylinder flow fields under motored operating conditions at 1500 rpm. Spatial and temporal flow velocity data has been presented for a 17.5 mm square region at 1.8 CAD intervals. The application of an increased resolution high speed DPIV technique has facilitated the calculation of an individual cycle average and ensemble average flow field velocity data. Comparison of cycle average and ensemble average velocities provided an indication of flow field cyclic variation. Further work on this application will allow the calculation of a cyclic variation parameter for each cycle and thus provide statistics on typical cycle to cycle variations at given engine operating conditions.

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