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27 A Simulation Study on the Effect of Inlet Valve Opening on Performance of High Speed Engines

Dimitar NOUHOV, Rui CHEN

Department of Aeronautical and Automotive Engineering, Loughborough University, UK

Variable camshaft phasing (VCP) system is a potential valvetrain technology for high speed engine applications since it does not increase the effective valve dynamic mass, which is essential to high speed operation. In addition, it is a relatively simple and low cost system. Inlet Valve Opening (IVO) is the start of valve overlap. It has significant effect on engine breathing. As part of a general assessment on the VCP system, such an effect was calculated and analysed using a zero- and one- dimensional based commercial engine simulation package, Lotus Engineering Simulation (LES) and reported in this paper. The simulation was based on a 0.6l, 4-cylinder, 4-stroke, high speed (up to 13500rpm), production spark ignition engine. It was found that IVO can either improve the utilisation of inlet charging effect or reduce backflow during the valve overlap period caused by speed related wave effects from the exhaust manifold.

Keywords: **High speed engine, Engine breathing, Engine simulation**

1. INTRODUCTION

Variable Camshaft Phasing (VCP) systems are currently the most popular active valvetrain systems due to their cost effectiveness and simplicity[1]. Because the valve spring dynamics are independent from the system, it has the potential for use in high-speed engine applications. Since high speed engines with fixed camshaft phasing have a larger compromise on valve timing than conventional engines, it is logical to assume that the performance improvement offered by VCP would be more significant. Previous studies on the potential of VCP systems were generally limited to engine speeds up to 6500 rpm. It was found that retardation of Inlet Valve Closing (IVC) at high speeds allows better utilisation of the dynamic after-charge effect[2]. Retardation of Inlet Valve Opening (IVO) was found to reduce backflow by reducing the valve overlap. Overall, advancing camshaft phasing benefits low speed volumetric efficiency and retarding camshaft phasing increases high speed volumetric efficiency[2]. It is worth mentioning that advancing or retarding camshaft phasing will change both IVO and IVC equally.

Previous research dedicated to IVO timing in low and medium speed engines suggests that the IVO should be sufficiently advanced to create enough flow area after Top Dead Centre (TDC) to reduce gas velocities and pumping loss[3]. Roth[4] correlated optimal IVO with Intake Pseudo Flow Velocities (IPFV) at TDC. It was found that IVO could be delayed significantly without loss of performance, and retarding IVO reduced backflow during the valve overlap period.

High speed engines have traditionally operated with large valve overlap. Consequently, the pressure gradient across the inlet and exhaust ports of the cylinder has a greater effect on volumetric efficiency. In such applications, the pressure gradient does not generate backflow at all engine speeds. IVO directly controls the valve overlap. It therefore has a significant effect on volumetric efficiency. In the research reported in this report, such influences were investigated using a commercial engine simulation code - Lotus Engineering Simulation (LES) Software.

2. SIMULATION
2.1. Simulation Code Description

In the simulation model employed for the investigation, the engine geometry is represented as a number of zero- and one- dimensional elements as shown in Figure 1. The cylinder and combustion chamber are modelled as zero- dimensional elements and there is no information about the in-cylinder fluid flow. Since the change of volumetric efficiency will not necessarily be proportional to an increase in IMEP, as combustion efficiency may not remain the same, volumetric efficiency is used in this study[5].
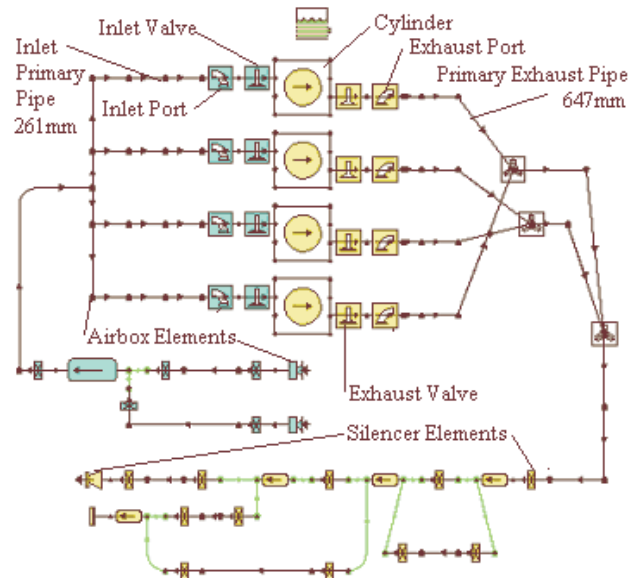

Fig.1 Engine model

2.2. Engine Specification

The engine modelled in this study is a high speed, 600cc, 4-stroke unit used in a production motorcycle. Its specifications are given in Table 1. In order to satisfy the performance criteria defined by its application it has been developed with emphasis on high maximum specific power output. This has compromised its low speed torque. The inlet and exhaust geometry is such that different tuning effects occur at a broad range of speeds.

Table 1 Engine specifications

Number of cylinders	4 in line
Bore / Stroke	68mm / 41.3mm
Number of inlet valves	8
Number of exhaust valves	8
IVO / IVC / Inlet max. lift	48°BTDC/80°ABDC/9mm
EVO/EVC/Exhaust max lift	62°BBDC/34°ATDC/8mm
Inlet primary length	261mm
Exhaust primary length	647mm
Max. engine speed	13500rpm

2.3. Model Validation

The software has been validated on a large number of production engines as well as the engine used in this simulation[6]. Figures 2 and 3 show the measured and calculated inlet and exhaust port pressure. The calculated parameters show the same trends as the measured data.
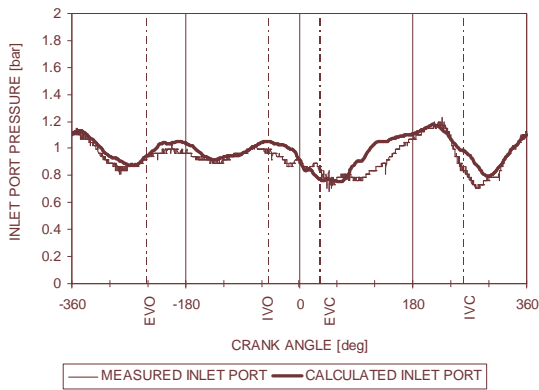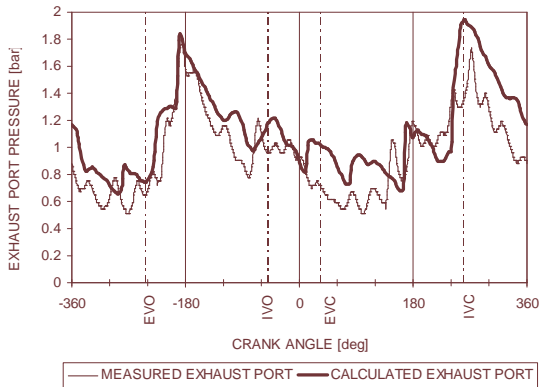

Fig.2 Inlet port pressure vs. crank angle

Fig.3 Exhaust port pressure vs. crank angle

3. RESULTS AND DISCUSSION

Five different IVO timings were calculated as detailed in Figure 4. In order to minimise the influence of variation of maximum lift and lift profile on the calculated volumetric efficiency, the lift profile from IVO to maximum lift was kept constant. A compensation for the reduced duration has been made by increasing the closing velocity immediately after maximum lift. IVC timing remained unchanged during the calculations.

Figure 5 shows the effect of IVO on calculated volumetric efficiency at ambient inlet conditions with various IVO timings. It can be seen that the volumetric efficiency curve generally consists of a series of peaks and dips. At speed around 2500rpm, 4750rpm, 6500rpm and 10000rpm, the volumetric efficiency peaks, and at around 1750rpm, 3500rpm 5750rpm and 9000rpm, the efficiency dips. The large dip in the volumetric efficiency in the region of 3500 rpm is a typical characteristic of many 4-cylinder high speed motorcycle engines. It seriously decreases the engine torque in this speed range. However, it is important to note that there are significant differences in amplitude among the peaks and dips when various IVO timings are employed. Advancing IVO increases the amplitude of the peaks and retarding IVO improves the dips. Such waveform effect is due to the acoustical behaviour inside the intake and exhaust port as well as the engine cylinder.
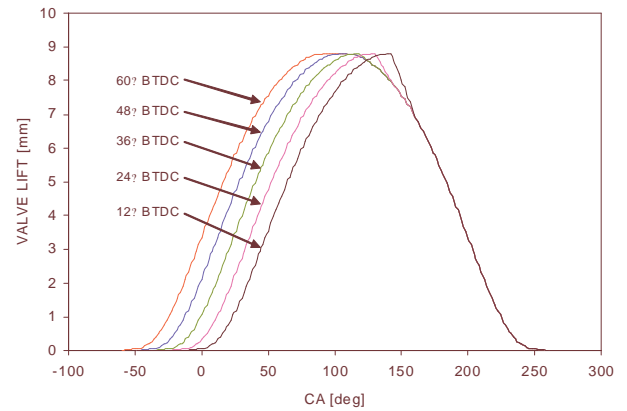

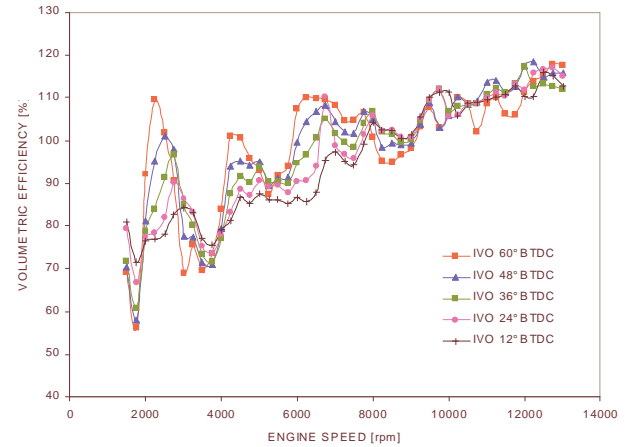*Fig.4 IVO timing employed in the calculations*

Fig.5 Volumetric efficiency vs. engine speed

To simplify the explanation, the term pressure gradient has been used in this report. A positive pressure gradient means that the instantaneous pressure in the inlet port is higher than that in the exhaust port, and the inverse has been defined as a negative pressure gradient. The acoustic effect in the inlet manifold is a wave caused by the depression during the initial part of the inlet stroke and reflected by the first junction at a much higher pressure. Depending on the engine speed and the primary length of the inlet manifold, this process may be repeated several times per engine cycle. Similar process takes place in the exhaust system.

In order to identify the part of the intake process which is most sensitive to IVO, the intake process has been divided into three periods: IVO to Exhaust Valve Closing (EVC) which is the valve overlap period, EVC to Bottom Dead Centre (BDC) and BDC to IVC. Figure 6 shows the calculated mass that has entered the cylinder through the inlet during each period. It can be seen that below 8500rpm the valve overlap period is most sensitive to IVO timing. Above this speed, the sensitivity is reduced due to the low pressure gradient across the cylinder. The mass that the engine inhales during IVC to BDC and BDC to IVC periods is found to be less sensitive to IVO. Once the exhaust valve is closed the mass flow in the cylinder becomes a function of the inlet and cylinder pressures.
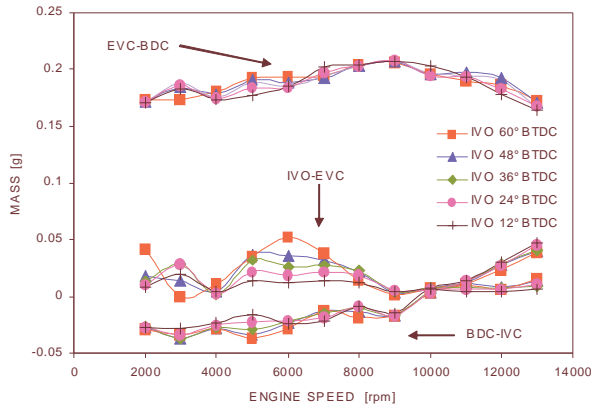

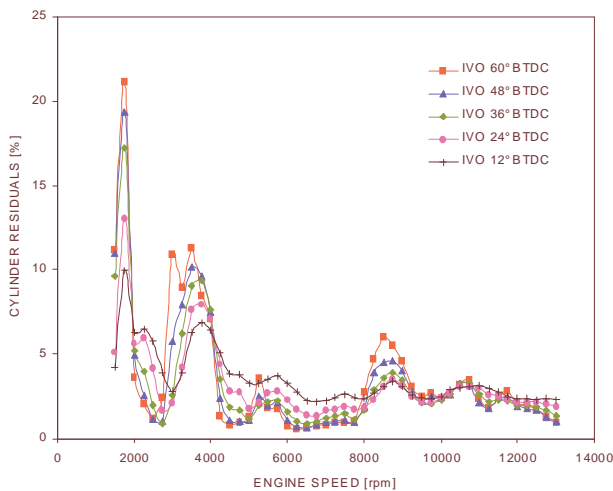*Fig.6 The mass inhaled during different periods of intake process at various engine speeds*

Fig.7 Exhaust residuals in cylinder after IVC

The role of the overlap is to replace the residual gasses from the previous cycle with fresh charge. Figure 7 shows the exhaust residuals in the engine cylinder after IVC for various IVO timings. It can be seen that the residual gases peak at the same speeds where low volumetric efficiency is experienced as showed in Figure 5. This proves that the dips in volumetric efficiency are due to the acoustic effect in the exhaust and inlet port during the overlap. When the pressure gradient is negative, backflow from the exhaust port occurs. Some of the burned gas, which has been initially expelled, flows back into the cylinder increasing the amount of residuals at certain engine speeds.
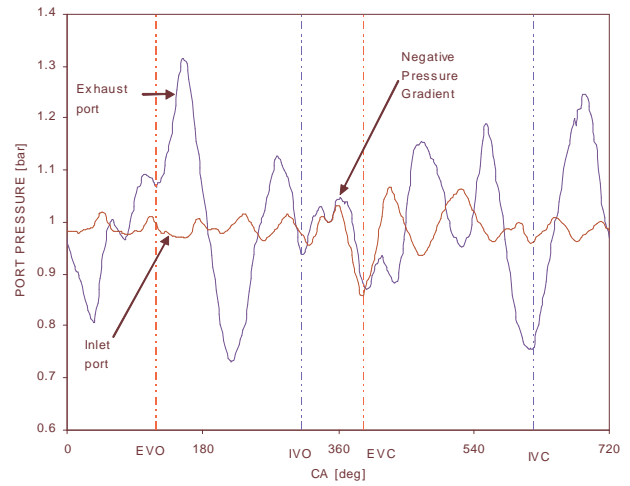

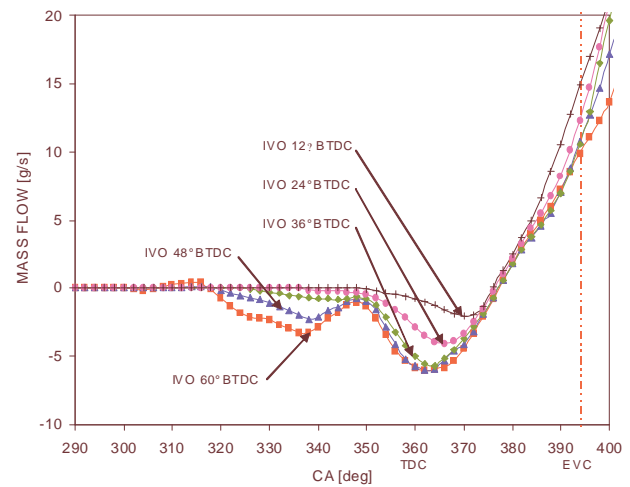*Fig.8 Calculated inlet and exhaust port pressure at 3500rpm*

Fig.9 Inlet mass flow rate with various IVO timing at 3500rpm

Figure 8 shows typical calculated pressure curves for the inlet and exhaust ports at engine speed of 3500rpm and IVO of 48° Before Top Dead Centre (BTDC). The same phenomenon can also be found at 1750rpm and 9000rpm where volumetric efficiency dips occur. It can be seen that during the valve overlap, the exhaust port pressure is generally higher than that of the inlet port. This is caused by the positive pressure pulse arriving at the exhaust port. Such a negative pressure gradient causes exhaust gas backflow and reduces engine volumetric efficiency. The backflow is affected by the IVO timing. Figure 9 shows the calculated inlet mass flow rate with various IVO timing at 3500rpm engine speed. It can be seen that more advanced IVO allows more exhaust gas backflow into the inlet port. This is because the available flow area during the overlap period increases as IVO advances. Consequently, the negative pressure gradient generates higher backflow.

When the speed changes the pressure gradient during the overlap period varies. Figure 10 shows calculated inlet port pressure at 6500rpm and IVO of 48° BTDC. It can be seen that the pressure gradient becomes positive. The same phenomenon can also be found at 2500rpm and

4750rpm where volumetric efficiency peaks occur. The positive pressure gradient is caused by the coexistence of negative pressure wave at the exhaust port and positive pressure wave at the inlet port. Figure 11 shows the calculated mass flow through the inlet ports with such positive pressure gradient. No backflow occurs. In these cases, early IVO can be used to fully utilise the potential of such positive pressure gradient to improve the engine's volumetric efficiency. However, a practical engine has a relatively short path between inlet and exhaust ports especially for the pent roof combustion chamber configuration. The effect of very early IVO will be diminished since some fresh charge may escape directly into the exhaust. The residuals purging effect is likely to be smaller.
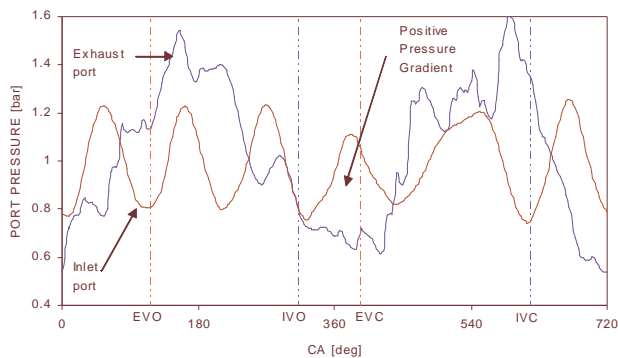

Fig.10 Calculated inlet and exhaust port pressure at 6500rpm
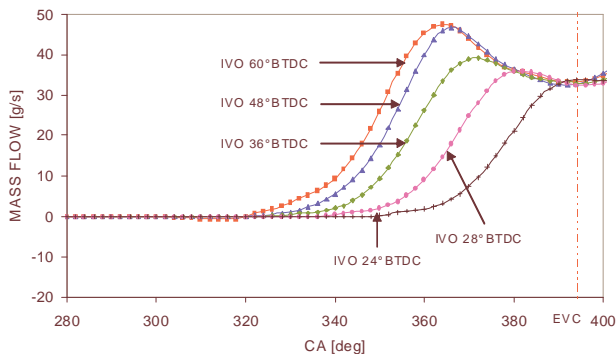

Fig.11 Inlet mass flow rate with various IVO timing at 6500rpm

Based on the model predictions, Figure 12 shows the optimal IVO timing varying within the range from 12° to 60° BTDC, which produces the highest volumetric efficiency. It is interesting to point out that 60° BTDC appears to be the optimal IVO timing for many engine speeds. It suggests that greater improvement may be obtainable if more advanced IVO timings were employed. However, in the actual engine, this is limited by the piston to valve clearance. For the engine considered in this report, 48° BTDC is the maximum advance that can be safely used. Figure 13 shows the possible volumetric efficiency improvement achieved by varying the IVO timing. It can be seen that varying IVO has the potential to improve both peaks and dips of the volumetric efficiency across most of the engine speed range. More importantly, it shows that the large dip in volumetric efficiency in the

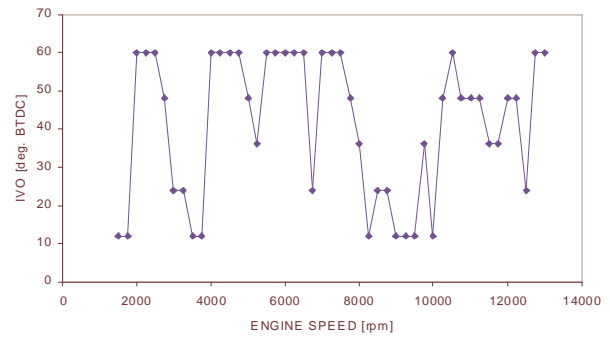speed region from 3000 to 4000 rpm can be considerably improved.

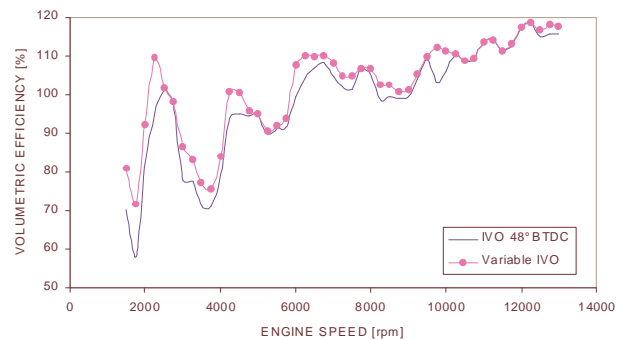*Fig.12 Optimal IVO settings in range (12-60° BTDC) for best volumetric efficiency*

Fig.13 Calculated volumetric efficiency with optimal IVO settings in range (12-60° BTDC) and constant IVO of 48° BTDC

4. CONCLUSION

The duration of the valve overlap influences the acoustic effect of inlet and exhaust manifolds on the intake event.

At engine speeds when positive pressure gradient across the cylinder during valve overlap occurs, an early IVO increases volumetric efficiency.

Whenever negative pressure gradient occurs, IVO needs to be retarded to improve the dips in the volumetric efficiency curve.

The ideal IVO timing fluctuates with engine speed. This is different from previously reported trends for ideal IVC. Therefore retarding or advancing the intake camshaft phasing may not always satisfy both IVO and IVC criteria.

Variable duration event combined with VCP will result in greater volumetric efficiency improvement.

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