Camcon Intelligent Valve Technology – a Powerful Tool for Combustion Development

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Abstract

Camcon's Intelligent Valve Technology (iVT) provides a full authority, fully flexible, electromagnetic poppet valve actuation system that includes fast feedback control of valve position throughout the valve event. It also offers unrivalled levels of independent and infinitely variable control over valve timing, period, lift and even lift curve shape.

Until recently, work on this technology has focussed on multi-cylinder applications with the ultimate objective of volume production – this work is continuing and has been described elsewhere [1]. However, the possibilities for using the technology purely as an R & D tool for combustion research, cam profile optimisation and more fundamental studies based on single cylinder research engines have now become apparent.

A standardised, "Generic" actuator has been developed, sized to provide an excess of available torque and thus the capability to deliver extreme events. This has made it possible to produce iVT single cylinder conversion kits readily adaptable to a wide range of cylinder head geometries. A set of generic actuators can be paired with a simple, custom designed, adaptor housing to mate the actuators to the client specific cylinder head.

This approach then facilitates dramatic improvements in single cylinder research productivity – not only allowing work that would normally take weeks, with multiple cylinder head rebuilds, to be completed within a couple of days but also improving data quality. The quality improvements arise from the fact that friction levels are undisturbed by rebuilds, a-b-a-b testing becomes a trivial matter rather than a time consuming chore. Furthermore, the possibility of anything else changing between tests and casting doubt upon any results is eliminated – the valve train test variables lift, timing, period, event shape, etc. can be adjusted without even stopping the engine! In fact, it is possible to switch the valve train from test condition "A" to condition "B" over the period from one cycle to the next!

In addition to the design and application of the single cylinder combustion and valve train optimisation tool, the paper also includes the following:

A summary of the operating principles of iVT

Rig test results from the latest generation actuator including exhaust valve capability

A brief review of the full multi-cylinder 16 valve iVT cylinder head package

1. .iVT Operating Principles

Camcon's iVT consists, in its simplest form, of an individual rotary electromagnetic actuator per valve which uses a single shaft, the rotor, featuring a set of permanent, rare earth, magnets at one end and pair of complementary cam profiles on the other. These cams, in turn, drive a desmodromic mechanism to positively open and close its valve . Conventional valve springs are not required and the angular position of the camshaft is subject to high frequency feedback control throughout every valve event. Compliance to prevent the mechanism locking up and limit the applied valve seat loads is supplied by a pre-loaded, uni-directionally active spring built into the desmodromic linkage.

Front and side elevations of the mechanism are shown in Figure 1. Defining the dynamic angular position and velocity of the rotor permits control of the valve event lift, timing, the event duration or period and even the shape of the event almost entirely independent of the crank position. Maintenance of timing accuracy and avoidance of valve clash is handled entirely within the software. Valve lift variation is achieved by rotating the camshaft to the desired lift and then reversing the direction of cam rotation.

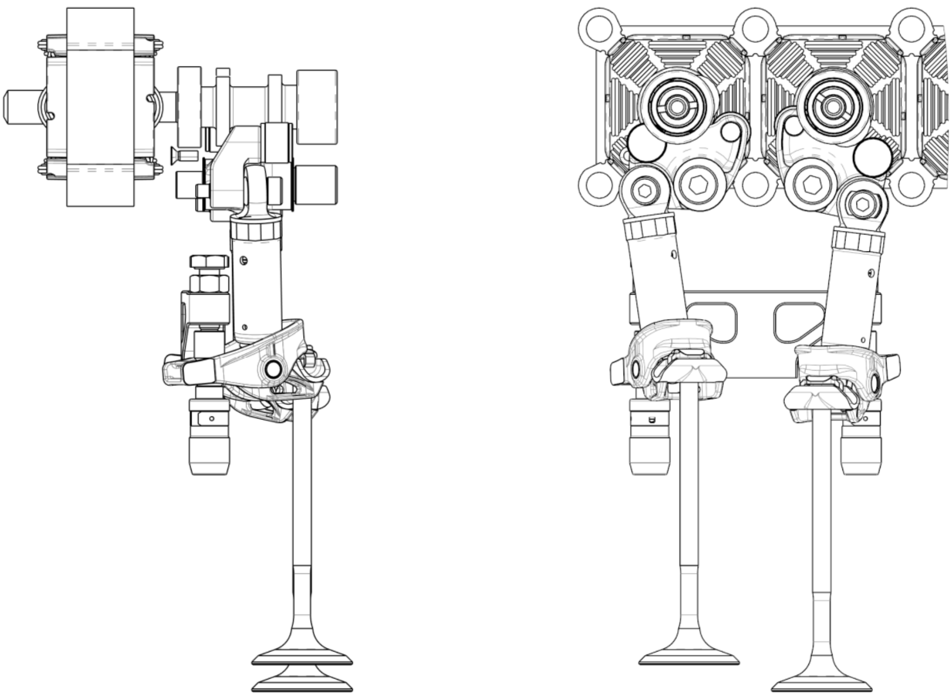

Figure 1: iVT mechanism, showing the mutli-cylinder Stator arrangement

Valve lift, timing and period are all infinitely and independently variable and are controllable without reference to the preceding or succeeding events – which means we can deactivate and reactivate valves on successive cycles, interpose subsidiary events between cycles and we have the scope for many more possibilities.

2. Evolution from and Integrated Multi-Cylinder Design to "Generic Single"

Optimisation of the design of an iVT actuator for a multi-cylinder, production intent system is a very different challenge from that posed in the case of a single cylinder engine (SCE) intended purely for research and development purposes. In the case of the former, cost, weight, inter-cylinder packaging space and electrical power consumption all loom large in the mind of the designer. In the case of an R&D SCE application however, the priorities change substantially. There are no adjacent cylinders constraining the available package space, piece cost is of much reduced significance, weight of little importance and electrical power consumption can be sacrificed in the interests of ensuring that sufficient torque is available to deliver the more extreme events that may be demanded in an R&D context.

On the other hand, it is important for reasons of in-field support and service parts availability that complexity is kept under control. Therefore, commonisation of electrical, electronic, electro-mechanical and other parts across a wide range of inherently different SCE applications is being pursued as far as possible. These different applications may differ in bore, in valve sizes, valve spacing and the included angle between the valves – the new, "generic" actuator needed to be able to accommodate all these differing parameters with zero or at least minimum customisation.

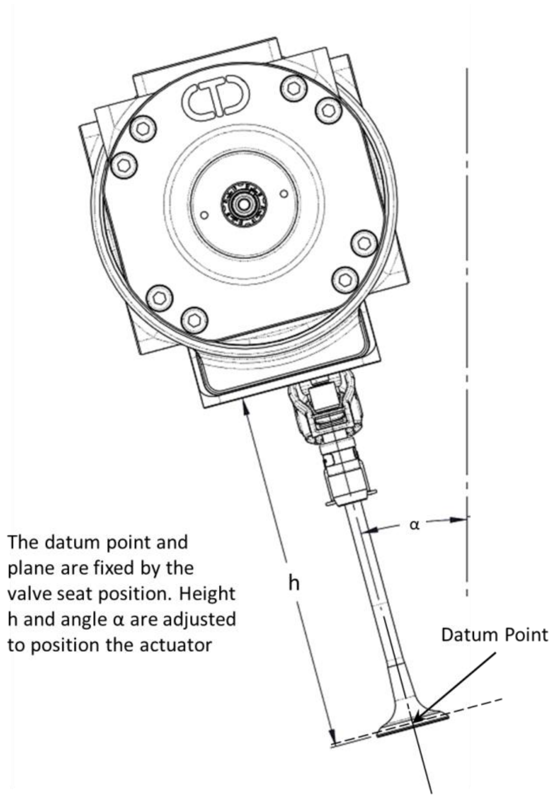

Figure 2: Arrangement of the iVT actuator relative to the poppet valve seat

Therefore, Camcon's objective was to design an individual actuator for each valve in such a manner that that each actuator can be positioned in space to accommodate the varying requirements of different cylinder heads/combustion chambers. In order to achieve this, the datum point for any actuator installation layout was taken as the centre of the circle forming the valve's gauge line diameter and the datum axis as the central line of the valve stem – which passes through the datum point itself. The actuator can then simply be positioned in space so that it lines up appropriately with the valve stem and is the required distance from the valve gauge line. The valve stem length is modified to position the actuator so that space for head bolt bosses, Hydraulic lifter installation etc. is provided. This is shown in Figure 2.

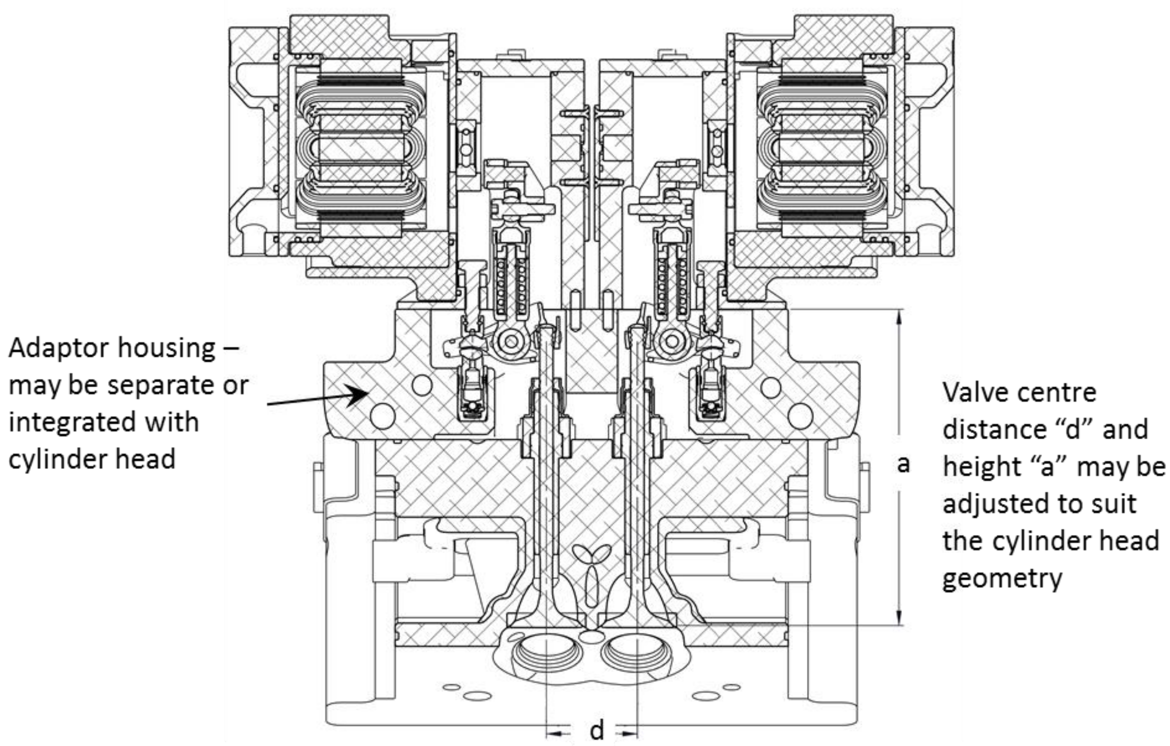

Figure 3: Arrangement showing valve centre distance and adaptor height variation

The simplest approach then depends on the cylinder head design, in the case of a cylinder head using a separate cam carrier arrangement, an adaptor housing can be substituted for the cam carrier. This adaptor housing is a simple component, unique to each cylinder head design, carrying the hydraulic lash adjusters, the location arrangement for the iVT finger follower and distributing the oil supply to the actuators. Figure 3 shows a layout of the arrangement and the dimensions which can be varied whist still using a common actuator assembly. In cases where the cam carrier is integral with the head, a new head must be used and which may feature an integrated adaptor housing or a separate one.

Figure 4 shows the common actuator design in section and Figure 5 shows the first off cylinder head with 4 actuators installed. This cylinder head is mounted on an Ø80mm by 90mm Ricardo Hydra now running at Brunel University, Figure 6

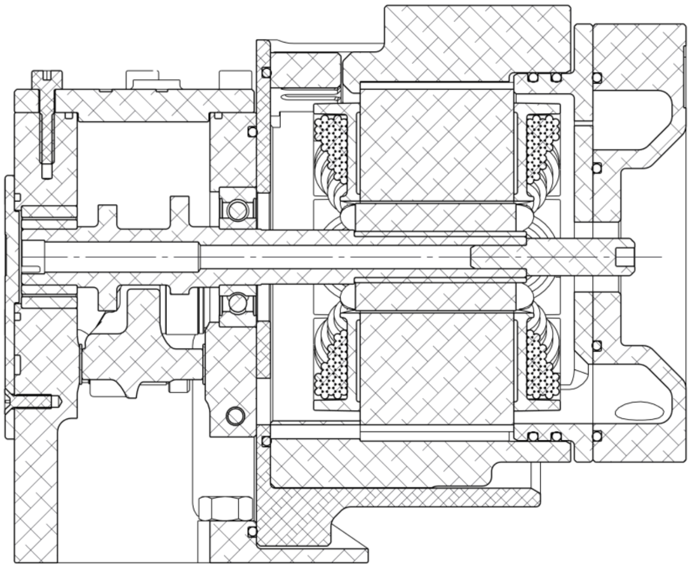

Figure 4: Section through the “Generic iVT Actuator”

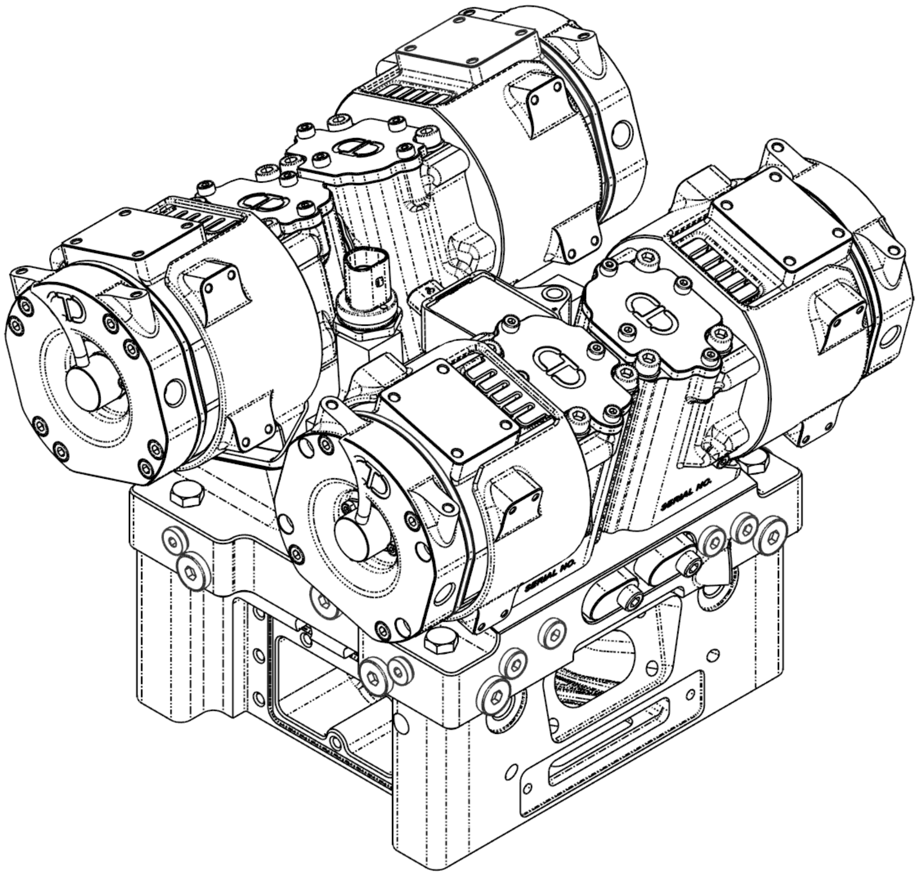

Figure 5: “Brunel” cylinder head assembled with 4 iVT actuators

Apart from the individual actuator packages as compared with the integrated modules previously used on the multi-cylinder engine, the other big difference between multi and single cylinder actuators is the stator assembly. The relaxation of package constraints means that the design can be simplified with common segments, symmetrical slots and a larger outside diameter. This, in turn, provides much more room for copper and, combined with a higher operating voltage – 48 volts instead of 12 - allows for a significant torque capacity uplift whilst reducing I^2R losses and therefore the cooling requirement.

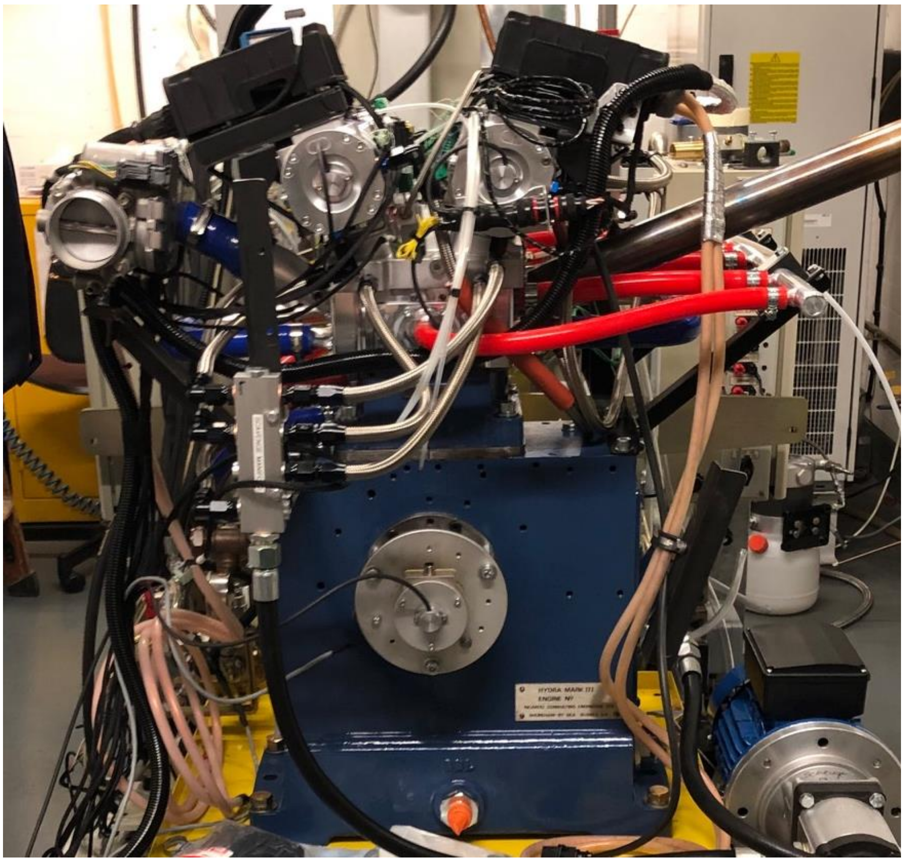

Figure 6: Ricardo Hydra engine with IVT Inlet and Exhaust actuators in process of installation at Brunel University

3. iVT Capability

iVT allows an unprecedented level of control over valve operation – the event phasing is infinitely variable within the constraints of valve-piston proximity or indeed, in some cases, inlet valve-exhaust valve contact. The event period and the valve lift are both infinitely variable and are adjustable virtually independently of each other. Furthermore, in the case of inlet valve events, the lift profile is controllable as shown in Figure 7.

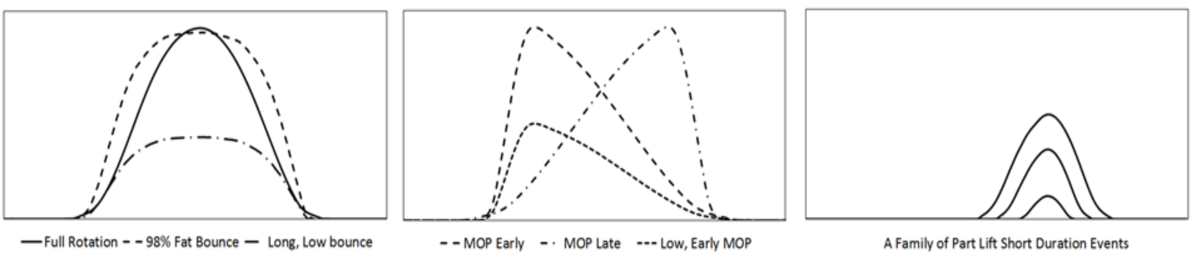

Figure 7: Some of the lift profiles achievable using iVT

In the case of exhaust valves, both the challenges and the desirable attributes are a little different, Camcon see flexibility in event phasing and period of exhaust events as very valuable but there is possibly less merit in lift variation and little in lift profile shaping. Therefore the current exhaust valve control strategies do not include a variable lift capability or an event shaping capability. Variable lift will be added in the future once concerns with respect to valve burning have been resolved.

The main challenge for exhaust valve operation is the additional force required to open the exhaust valve against the in-cylinder pressure at exhaust open timing. This necessitates a larger capacity actuator than the inlet valve and some changes to the control strategy but, for the purposes of this Generic Actuator design, a common inlet and exhaust actuator is employed.

In order to allow cost effective development of the exhaust valve control strategies a rig was designed and built which permits gas loading on the valve without the need for a fired engine test cell. A drawing of the rig is shown in Figure 8 below, the construction is quite simple with compressed air at a supply pressure of up to 14 bar fed into a fixed volume chamber, through an conventional inlet valve arrangement, from a large compressor. The test iVT unit is mounted to operate the exhaust valves dumping the air, via a silencer, to atmosphere. Note that, as shown in the diagram, an actuator from the multi-cylinder programme is shown rather than that of a “generic single”. However, the rig is easily convertible to make use of generic single actuators

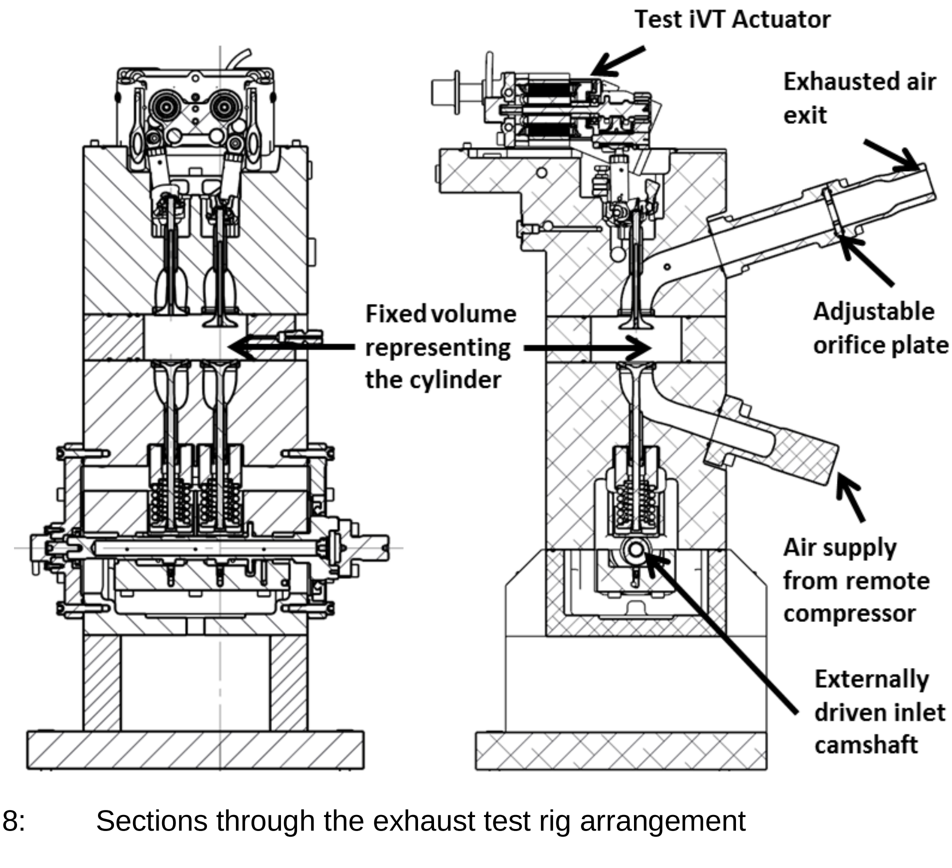

Figure 8: Sections through the exhaust test rig arrangement

Whilst the arrangement is not a perfect reflection of the situation in a firing engine, it is certainly sufficient to provide useful data both on the performance of the actuators themselves and on the effectiveness of different control strategies for the valve events. The rig will run up to 6000 Engine RPM equivalent and successful events at pressure differentials of 13 bar across the valve have been achieved at high speed. A typical set of results curves is shown in Figure 9.

This rig allows the testing of different control strategies, alternative actuator geometries and differential pressures (δP) that would not be easily attainable on the available test engine. All this is achieved quickly, simply, cheaply and without placing a firing engine at any risk. As such it has proven a valuable development tool for this technology

Of course, the acid test is application of the system to a real engine and results from the Brunel single are shown in Figure 10 At the time of writing, this engine was still being commissioned but results so far have been very satisfactory.

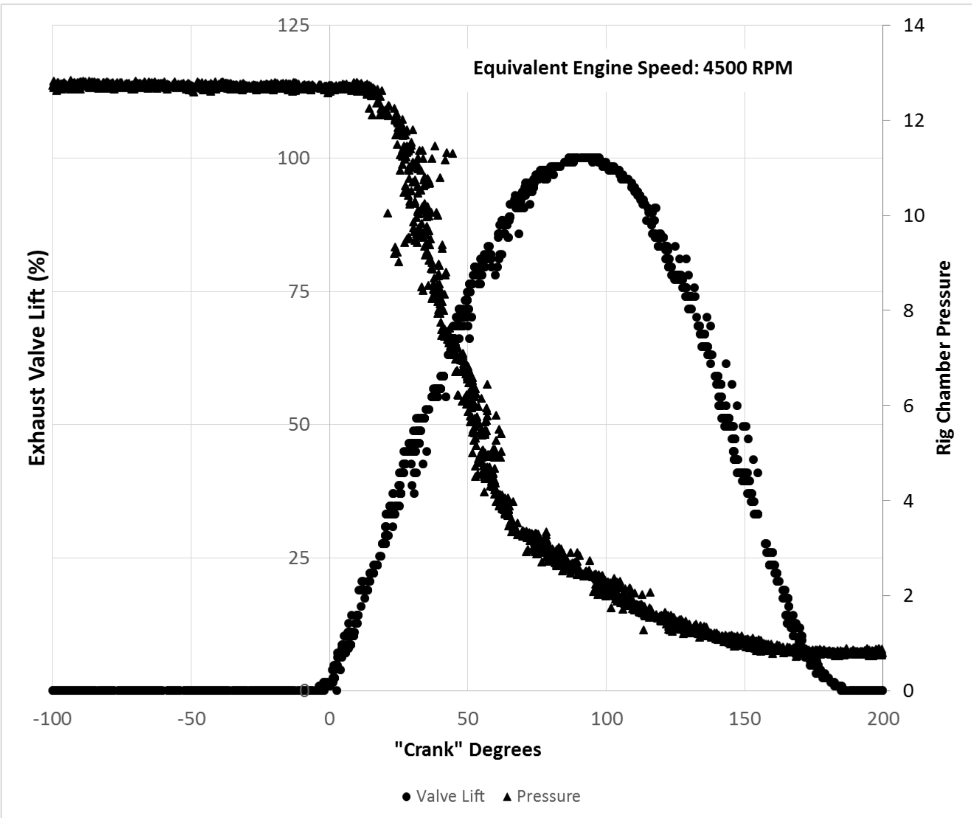

Figure 9: Sample Exhaust valve rig results, δP >12 bar, 4500 ERPM

4. Development Opportunities Permitted by iVT

The R&D potential afforded by the flexibility of the iVT system falls under a number of headings; the first is testing productivity, the next is data quality and the third opportunity afforded by iVT is the ability to run valve operating regimes that are simply not available from more conventional valvetrains. Let us consider these in turn:

Productivity: The opportunity provided by systems such as iVT is significant, even if the researcher's objective were simply to investigate the optimisation of a purely conventional valve train over a range of speed/load sites. The full range of lift, valve period and valve phasing – on both inlet and exhaust valves - can be studied very largely under fully automated control with the engine stopping only at the end of test shifts! Furthermore, because the testing can be completed so quickly as compared with conventional approaches, the parameters of interest can be explored in finer granularity and over a wider range – permitting more detailed and accurate response surfaces to be generated in the DoE software – and the optimum values output from that software can be run immediately without waiting for new hardware.

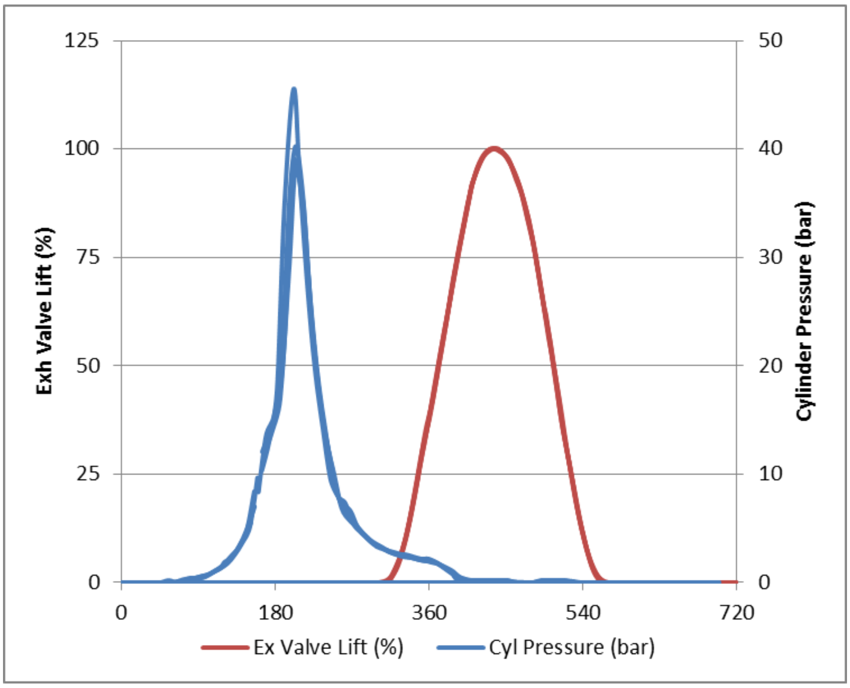

Figure 10: Initial results from the Brunel Single cylinder engine showing the cylinder pressure and exhaust valve lift curves

Data quality: These systems permit improvements in data quality in a number of ways. Firstly, it is much easier to run a daily check of a datum condition or conditions to ensure that the base engine condition has not changed. Because there is no need to change valve train hardware the original datum points can always be re-run at a moment's notice. Secondly, it is possible to run tests that would normally imply a hardware change on an A-B-C-A-B- C basis without even stopping the engine. This can only help to maintain the integrity of the test data. The fact that more test points can be included within the same time period – as mentioned under productivity – also has a positive effect on data quality, simply because the data density is higher and the resulting model derived from DoE techniques can be of higher resolution over a range of variables.

Operating Regimes: As an example, one of the simplest unconventional regimes which iVT allows is valve deactivation. Whilst this could also be achieved by more conventional hardware modifications or even multiple component swaps iVT allows the changes to be made at a moment's notice – even on alternating cycles.

There are other operating possibilities that would not be practicable using even advanced conventional systems, as each and every valve can be allocated its own specific event independently. Valve lift, phasing and period can all be independently varied. The lift curve shape itself can be adjusted – at the simplest level simply by "skewing" the lift so that the maximum opening point occurs early or late in an otherwise conventional lift curve. Alternatives include "flat top" events and various other options. Events can be omitted or, within limits, extra events can be inserted.

Essentially, valve events to be investigated are no longer limited by the constraints of mechanical possibility or testing costs and timescales but by the imagination of the development engineer.

5. Combustion Parameter Control

Clearly, even assuming symmetrical valve and port geometry, iVT offers the potential for optimising the "conventional" valve event parameters at every load/speed condition – valve opening and closing timing on both inlet and exhaust valves, plus lift on the inlets. However, the fact that this optimisation can be made for any and every speed/load point – and repeated to re-optimise for different target parameters (bsfc to NOx for example) all without hardware change would be a huge advantage on its own. But there is a much greater capability that can be used for broader studies and research.

The possibilities for control of combustion parameters are significant; the fact that such valve control systems can run different events (or no event) on each inlet valve for example allows us to not only to vary the general air motion regime in the cylinder from tumble to swirl and any degree of "swumble" in between but also to control the intensity of that motion. Identical events on both inlet valves deliver a tumble regime. However, we have extra control because, as engine speed reduces, we can maintain tumble energy by increasing gas entry velocity using lower lift and/or a shorter valve period. Swirl is achieved simply by deactivating one valve and the swirl direction can be reversed by changing valves. If we run dissimilar events on each inlet valve then we can achieve "swumble". Furthermore, we can select the two independent valve events with respect to phasing, period and lift – so that the requisite trapped mass and air motion is achieved at minimum pumping loss.

Clearly, extreme EIVC and LIVC conditions can be studied with the opportunity to optimise the entire inlet and exhaust event at each speed/load condition considered and all without any hardware changes.

However, there are other possibilities; for instance, at lower speeds, single exhaust valve actuation may be perfectly adequate to scavenge the spent charge but there may be a detonation borderline advantage in alternating the exhaust valve operation between valves. This could be because the exhaust valve temperatures would drop and therefore the heat transferred to the charge would be reduced. Another possibility would be to introduce an additional exhaust event at some point during the induction process to provide hot EGR – perhaps for CAE/HCCI purposes.

Another possibility, not strictly pertaining to combustion control, might be to use separate exhaust ports for each exhaust valve and then to employ different valve events on each port, as suggested by Roth et al [2, 3]. This combination of separate ports and differential exhaust events offers a number of potential benefits including allowing EGR to be taken from either early or late exhaust gas – which have different levels of HC.

6. Combining iVT with Cylinder Head Asymmetry

Another potential manner in which this technology may be used is in combination with asymmetric features within the cylinder head or manifolding. Reference has already been made above to separating the exhaust ports and the EGR potential but this can also be used with appropriate manifolding to direct high energy, high pulse intensity exhaust to the turbine whilst directing later exhaust gas direct to the catalyst – eliminating the need for a wastegate, reducing exhaust back pressure and providing opportunities for fast catalyst light off by re-directing gas depending on coolant temperature for example.

Further possibilities exist with respect to inlet porting and chamber design. One example stems from the significant improvements to burn rate that have already been demonstrated at low speed/load by deactivating one inlet valve and using swirl rather than tumble (coupled with higher velocity in the incoming charge) [1]. These improvements were secured with the original central sparking plug position. It is likely that further benefit might be possible if two plugs were used – one in the existing position and another offset to one side – or even displacing both plugs to mirrored offset positions.

Inlet port geometry could be adjusted so that there was a different emphasis on specific flow regimes for each port – even differential valve sizes could be considered. Figure 11 shows a comparison of the Mean Inlet Gas Velocities (MIGV) against engine speed for a layout with equi-sized inlet valves and for a layout with a significant difference in valve size – from which it can be seen that even higher gas velocities can be promoted at very low speed by using the smaller inlet valve, whist maintaining this advantage without unacceptable pumping loss by switching to the larger valve as the engine speed increases.

Ultimately, of course, both valves are used – and have the equivalent flow area to the original engine's valve arrangement. Of course, MIGV is only an approximate indicator for the kinetic energy of the induced charge – but this does give an indication of capability absent from other systems.

Similarly, in addition to routing options for the exhaust ports, differential valve sizing could also be applied to the exhaust valves themselves. This would be an especially complex optimisation challenge and would be particularly benefitted by 1D analysis before committing to hardware – but much validation work could be completed on a single, confirming the software model's accuracy before application to multi-cylinder testing.

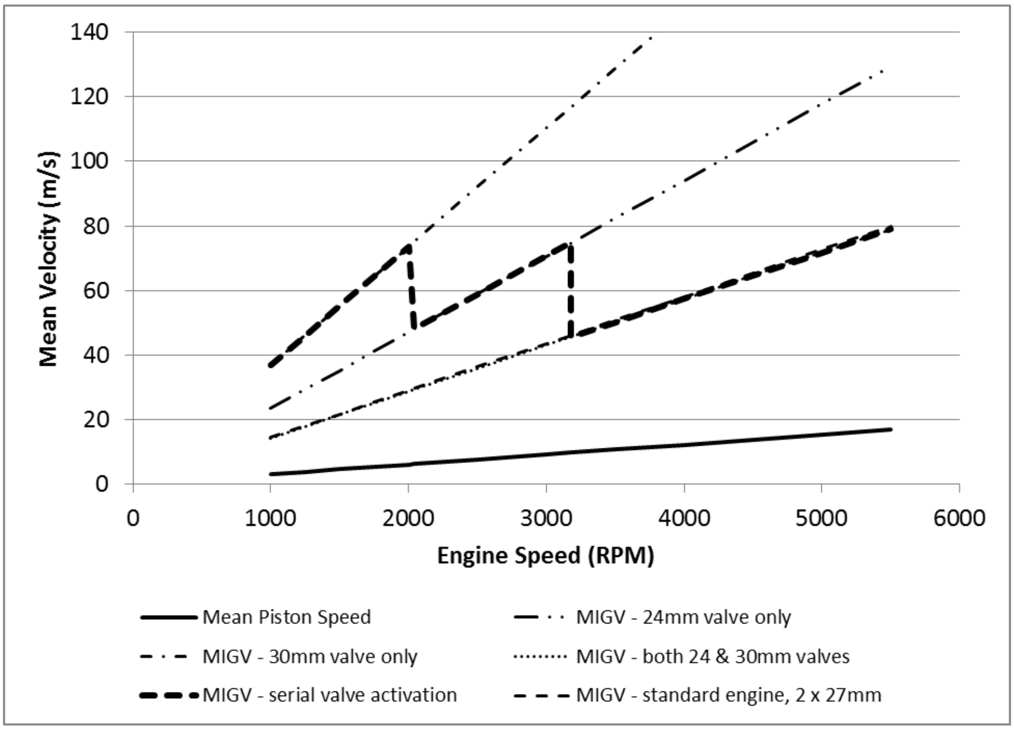

Figure 11: Effect of using 1 x 30 mm and 1 x 24 mm inner seat dia inlet valves plus a serial valve switching strategy as compared with 2 x 27 mm valves (equivalent total area)

7. Conclusions

The flexibility offered by iVT equipped single cylinder research engines offers unprecedented opportunities for extending, improving and accelerating combustion research at a time when the industry most needs it. The wide availability of this technology both in single and multi-cylinder form to aid combustion development is timely. Clearly, engine calibration becomes an ever greater challenge as more control variables are made available. Exploring the effect of these variables in a single cylinder environment will accelerate understanding and therefore our ability to exploit these capabilities in order to meet the challenges of the coming years – and to demonstrate that an optimally engineered hybrid vehicle will, in the medium term at least, have a lower "Dust to Rust" carbon footprint than is likely using pure BEV technologies.

Whilst this paper has concentrated on the availability and application of Camcon's iVT technology for single cylinder R&D engines, work continues on multi-cylinder applications with a view to eventual production applications. Figure 12 shows a CAD model of the package for an inlet plus exhaust iVT installation on the Jaguar Land Rover Ingenium 4 cylinder engine. Note that, whilst package width is increased, the height, in comparison with the standard engine, is reduced. Figure 13 shows a section through the cylinder head assembly showing the package of the iVT actuators and valve train into the cylinder head.

Figure 12: 16 valve, 4 cylinder in-line iVT package – based on the Jaguar Land Rover Ingenium engine

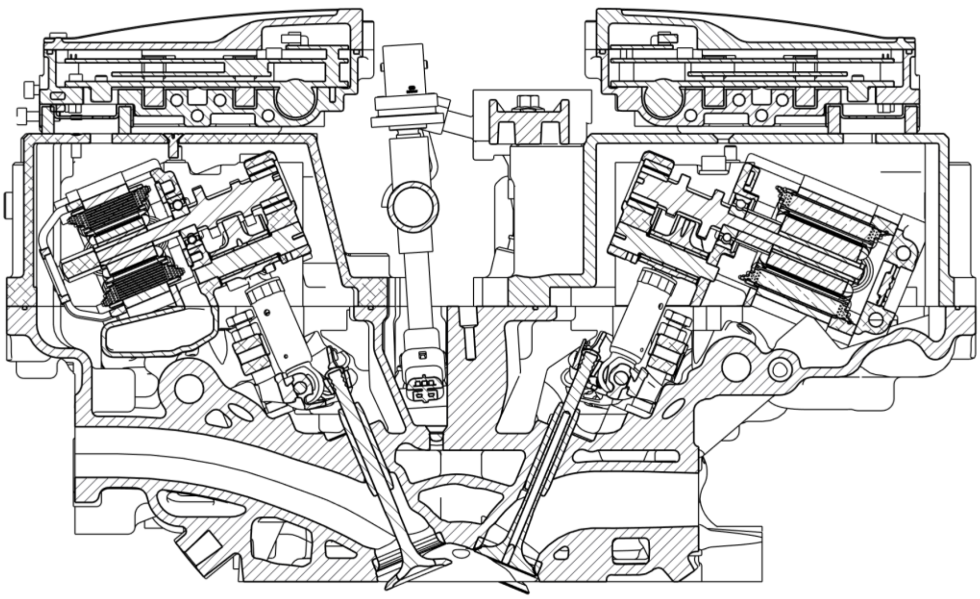

Figure 123 16 valve, 4 cylinder in-line iVT package - cross section through the cylinder head

The challenge facing the automotive industry at present is prodigious – whilst it is clear that pure internal combustion engine vehicles will lose market share rapidly over the coming years, there are many reasons why full electrification is decades away regardless of any CO_2 reductions. Therefore, the market for hybrids is likely to be very large – and it will be important that appropriate IC engines are not only available but re-optimised to permit even closer integration into the hybrid powertrain. The author does not believe that these engines will be simple range extenders but will be wide speed/load range engines even more highly developed that those we see today – iVT equipped research engines can contribute to the optimisation of those powertrains.

References

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